Viscous Free-Surface Flows

Vatsal Sanjay

European Research Council
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Physics of Fluids

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Link: https://youtu.be/3FZPkWxprDM

Collaborators & Acknowledgements

- **Detlef Lohse**
- Pierre Chantelot (Institut Langevin)
- Mazi Jalaal (UvA, Amsterdam)
- **Uddalok Sen (WUR, Wageningen)**
- **Jacco Snoeijer**
- **Cunjing Lv (Tsinghua Univ.)**
- **Alexandros Oratis**
- **Vincent Bertin**
- Youssef Saade (Canon)*
- Mandeep Saini*
- **Pallav Kant (Univ. of Cambridge)**
- Jonathan Pham (Univ. of Kentucky)
- Doris Vollmer (MPI-Mainz)

Canon

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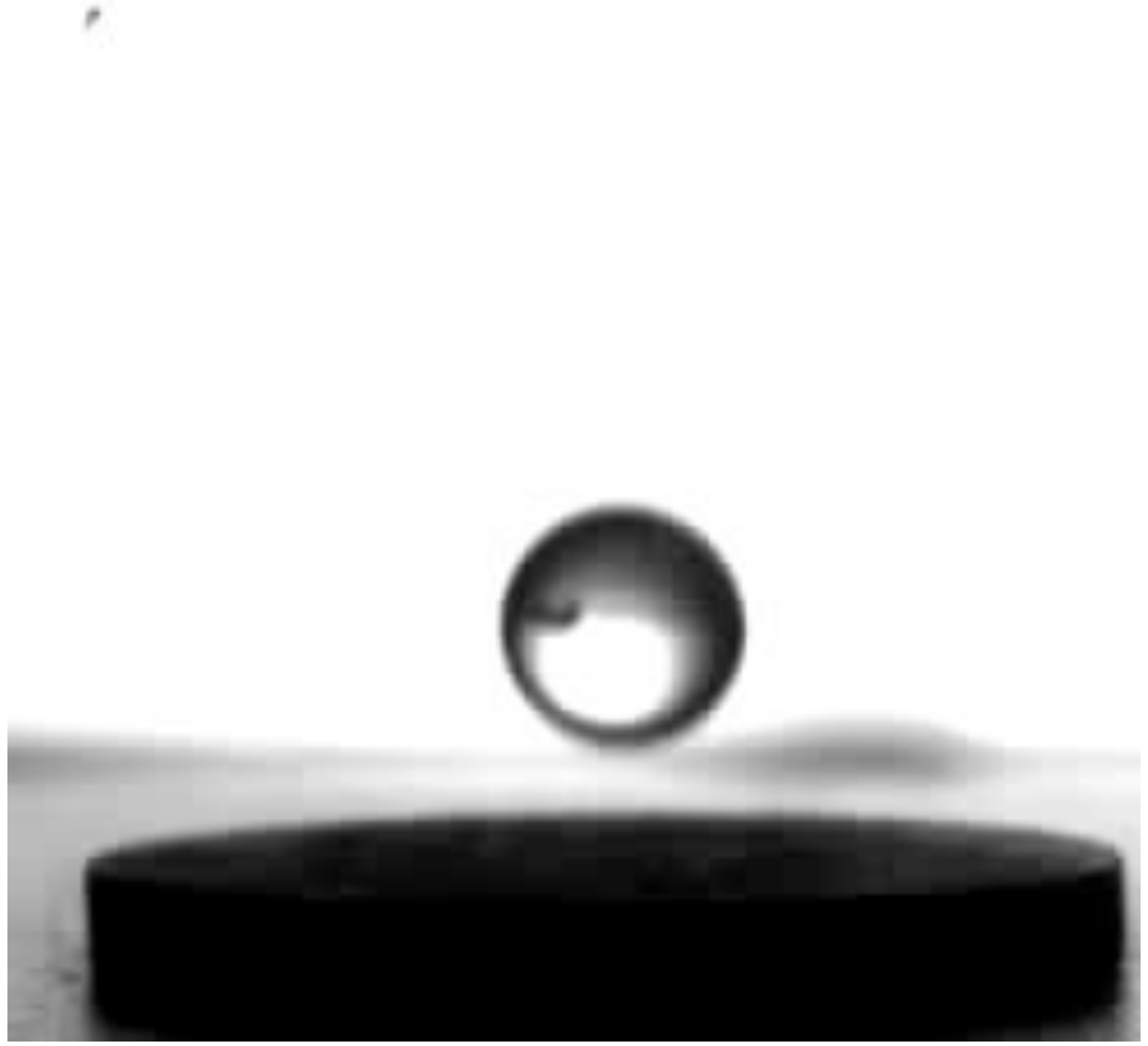
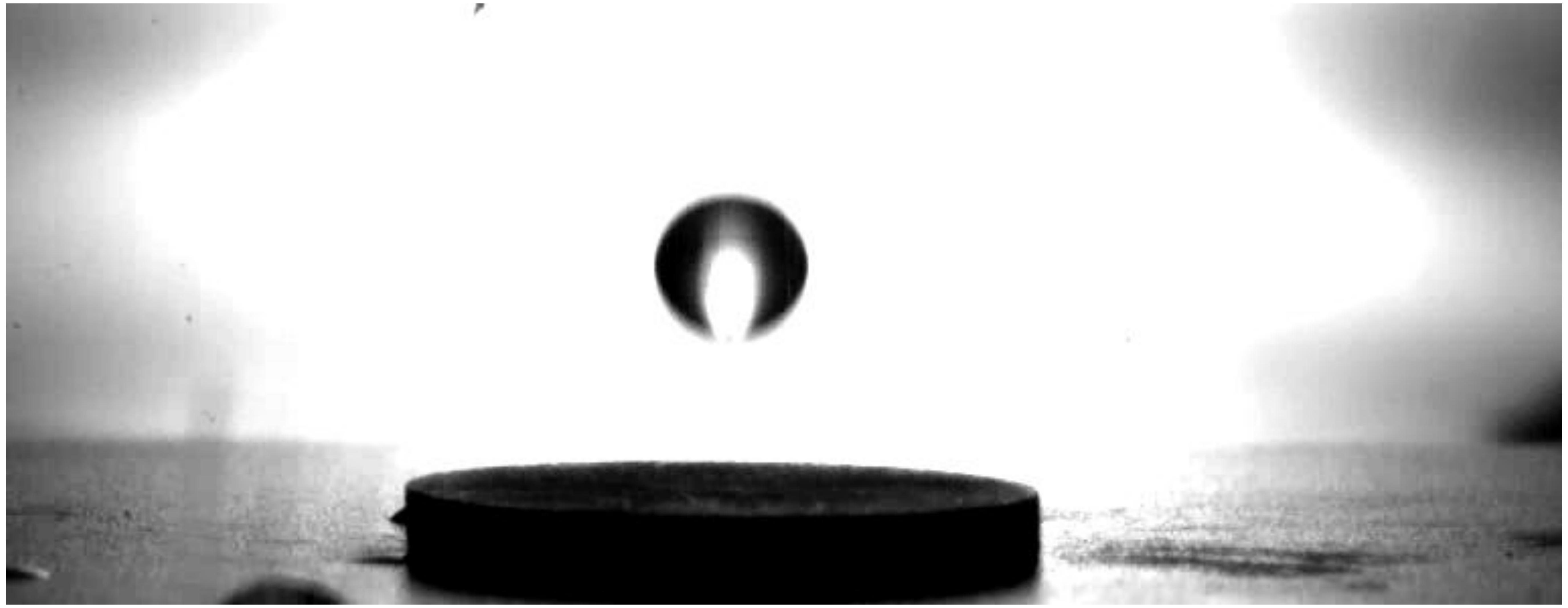
Drop impact on a superhydrophobic surface:
What are the forces exerted on the substrate?



low velocity



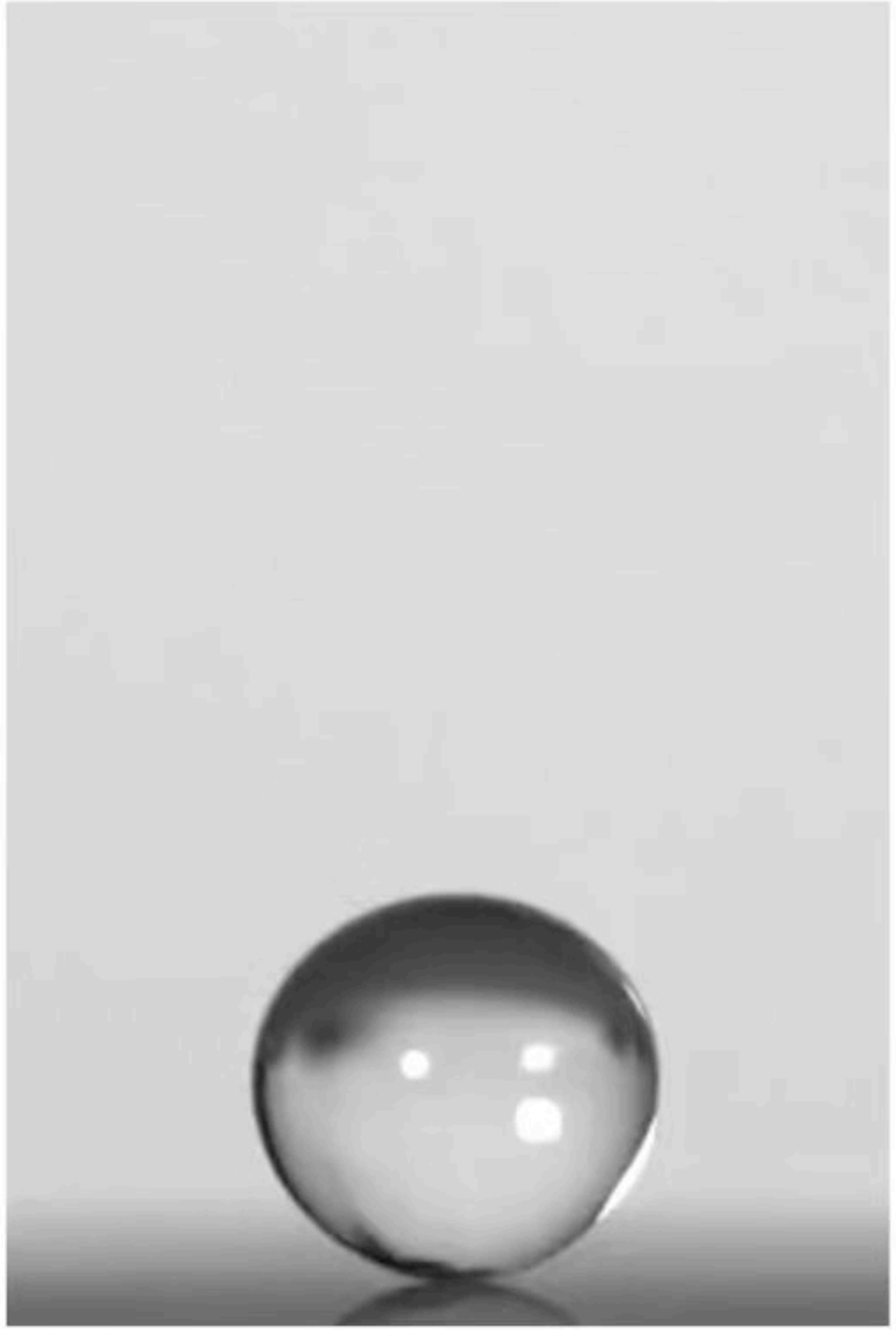
high velocity

Tsai, Pacheco, Pirat, Lefferts, Lohse,
Langmuir 25, 12293 (2009)

Parameter space of drop impact

- Velocity
- Diameter
- Viscosity
- Density
- Surface tension

- Surface roughness
- Temperatures
- Ambient air pressure
- ...

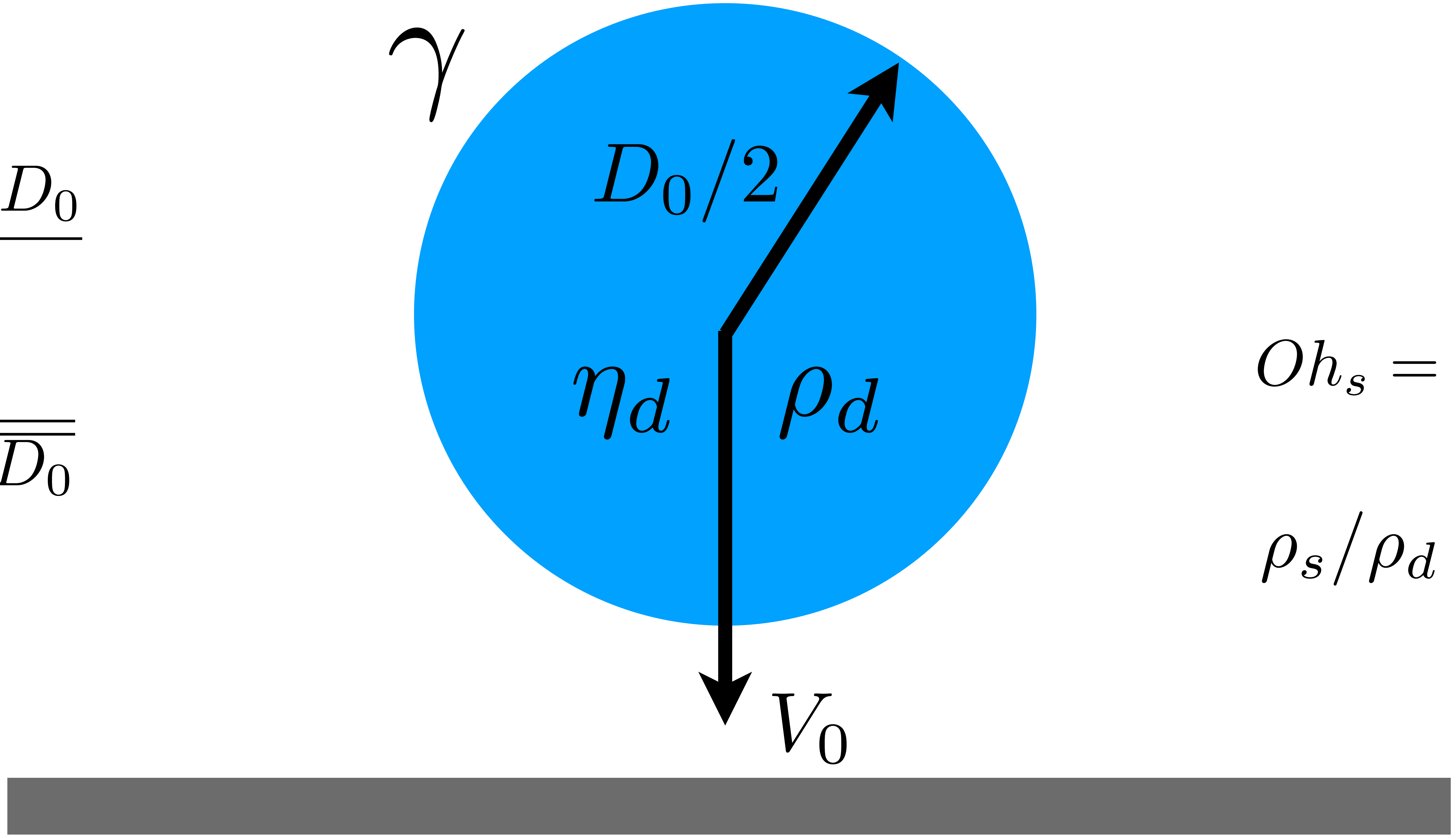


Viscous Free-Surface Flows

Drop Impact onto a solid surface

$$We = \frac{\rho_d V_0^2 D_0}{\gamma}$$

$$Oh = \frac{\eta_d}{\sqrt{\rho_d \gamma D_0}}$$

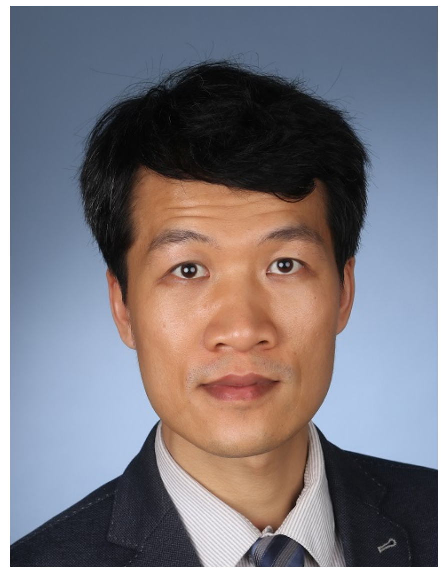


$$Oh_s = \frac{\eta_s}{\sqrt{\rho_d \gamma D_0}} = 10^{-5}$$

$$\rho_s/\rho_d = 10^{-3}$$

Superhydrophobic substrate

C. Lv



B. Zhang

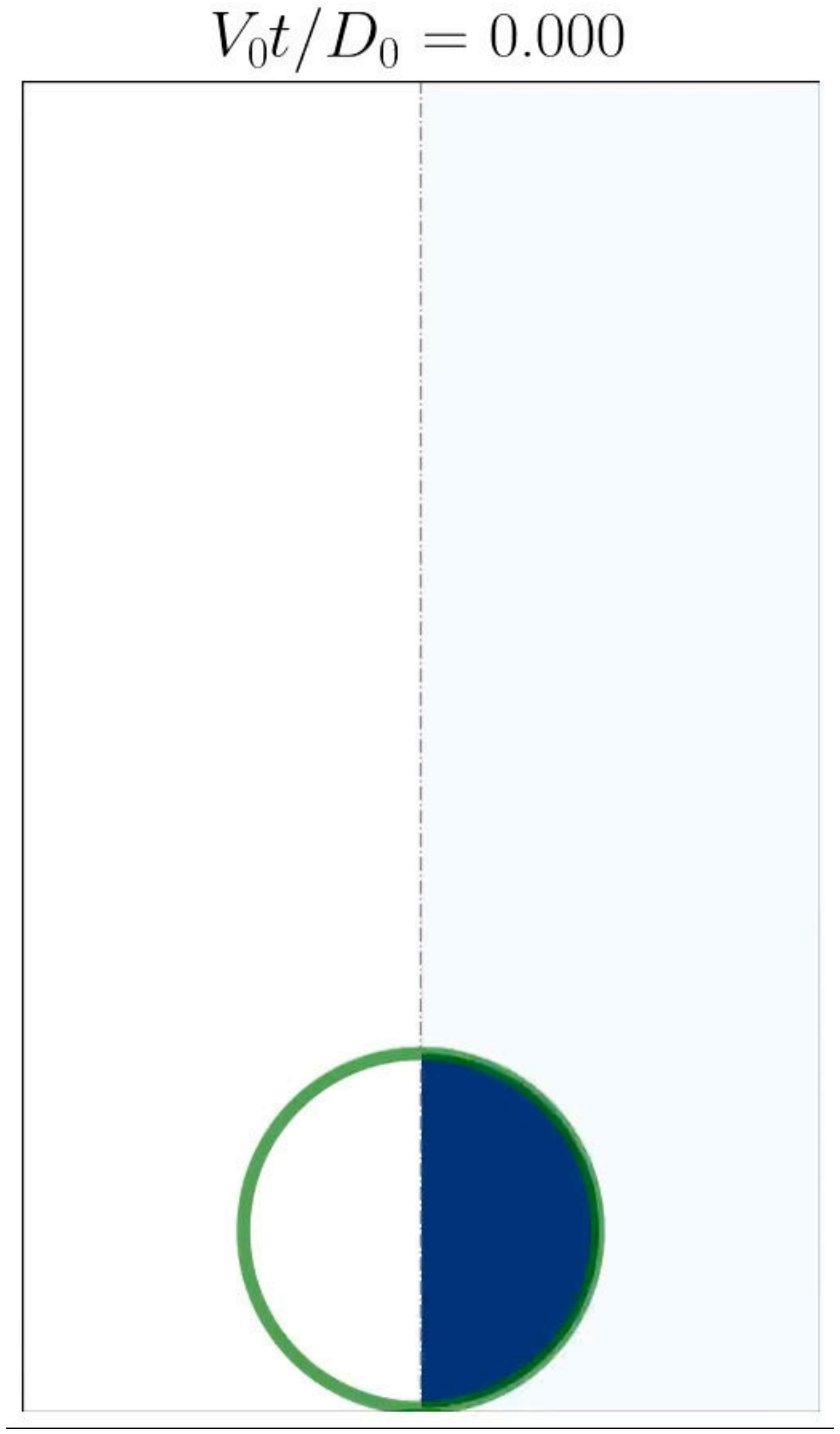
D. Lohse

How does it look like?

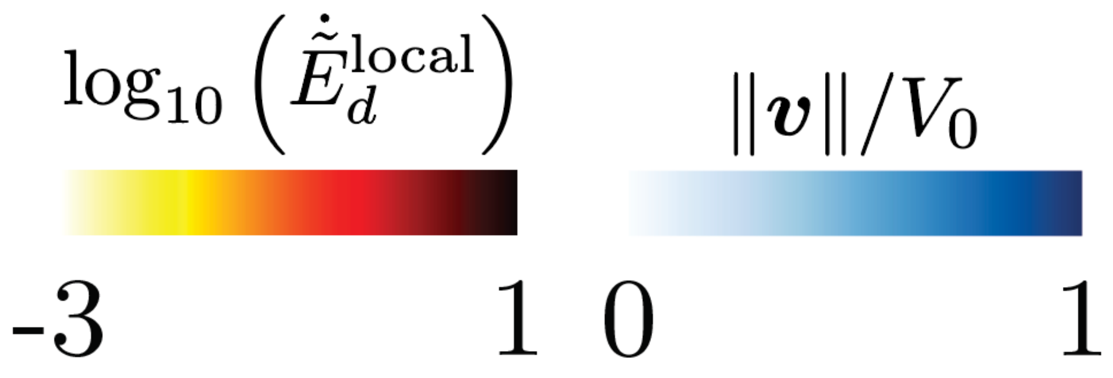
Volume of Fluid Method:
Basilisk-Code

Stéphane Popinet *et al.*

$We = 40$



- Impact
- Spreading
- Recoil
- Take-off

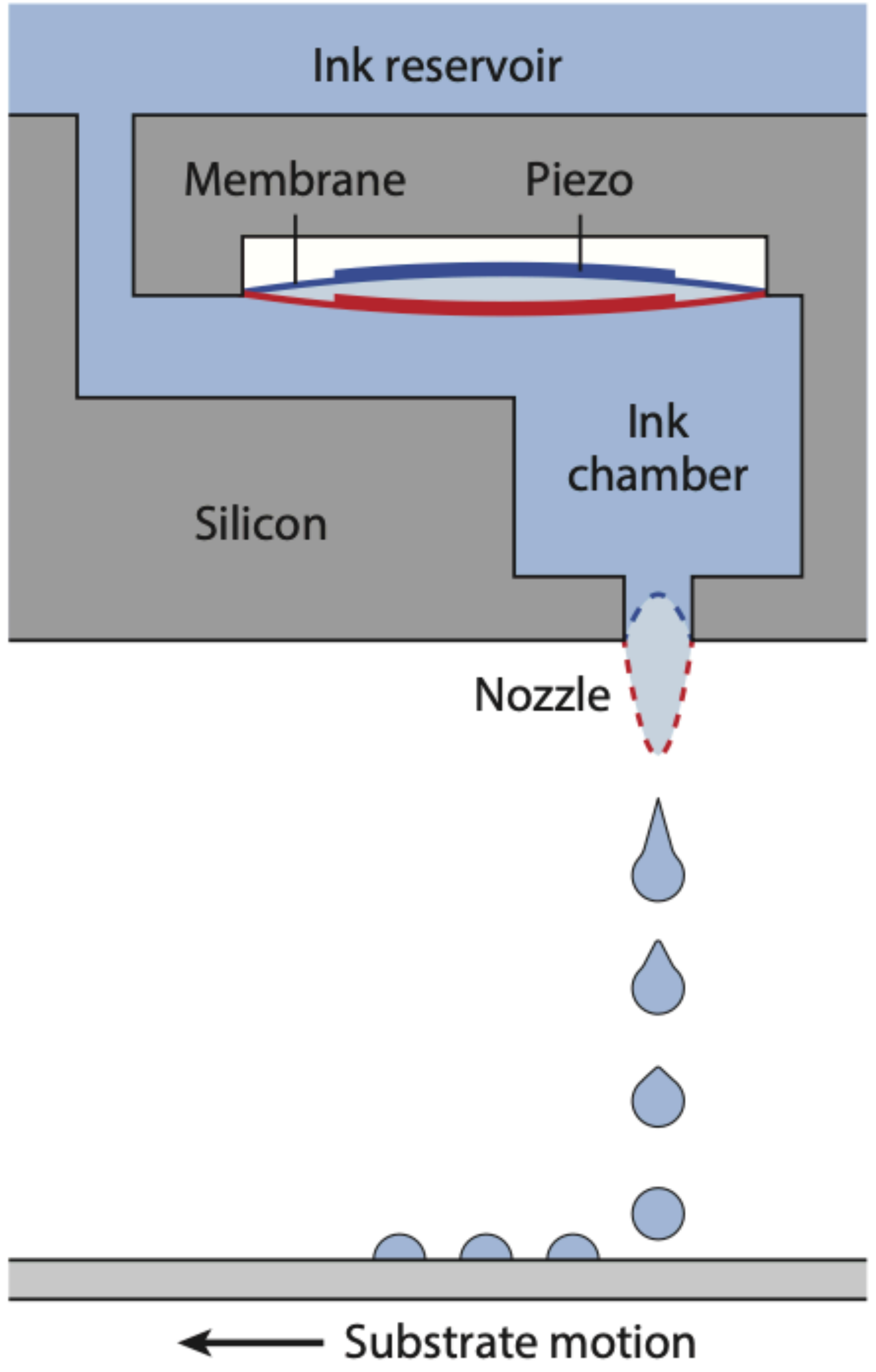


$$\dot{E}_d^{\mathrm{local}} = 2\eta\left(\boldsymbol{\mathcal{D}} : \boldsymbol{\mathcal{D}}\right)$$

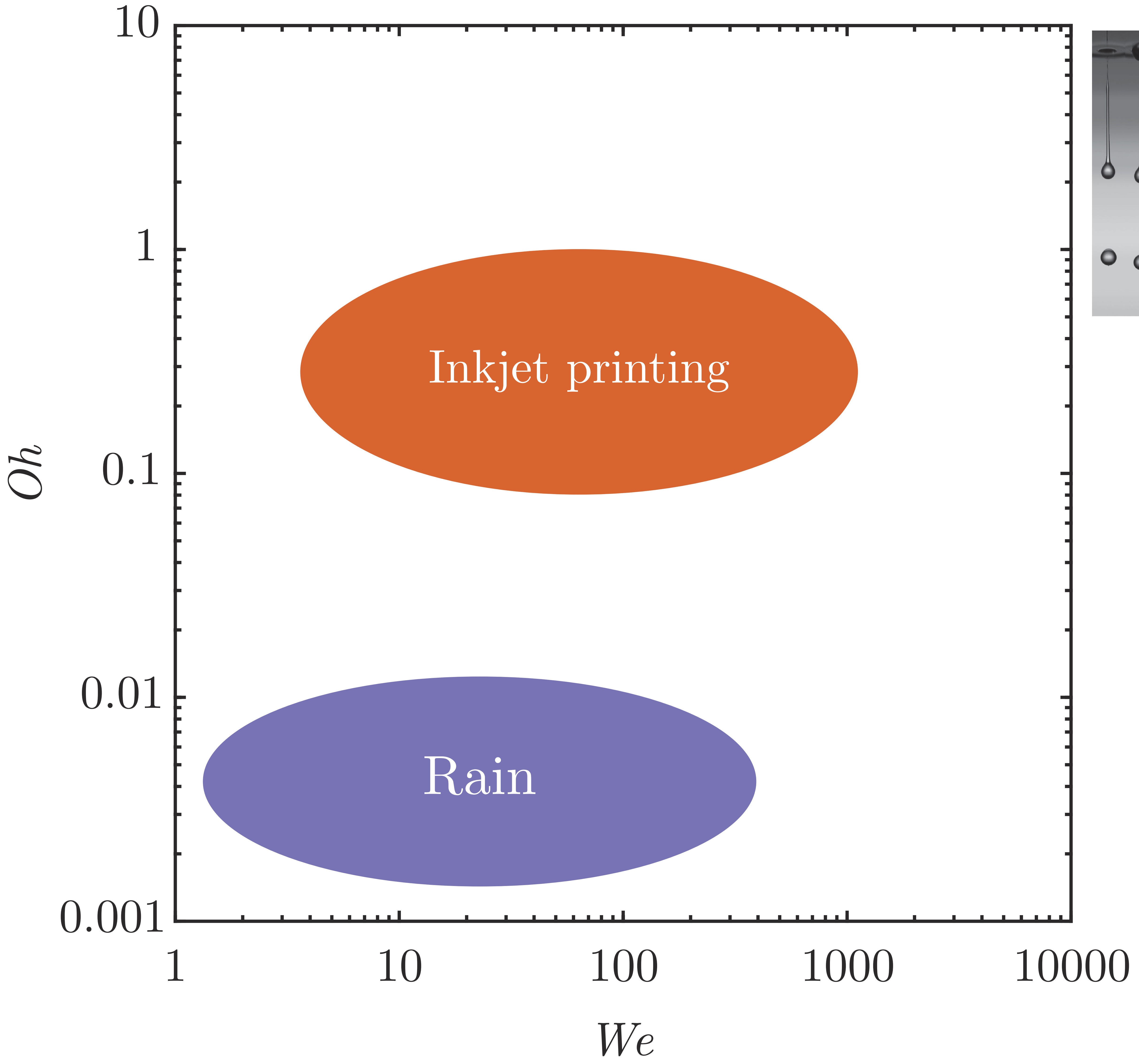
$$\boldsymbol{\mathcal{D}} = \left(\boldsymbol{\nabla v} + \left(\boldsymbol{\nabla v}\right)^{\mathrm{T}}\right)/2$$

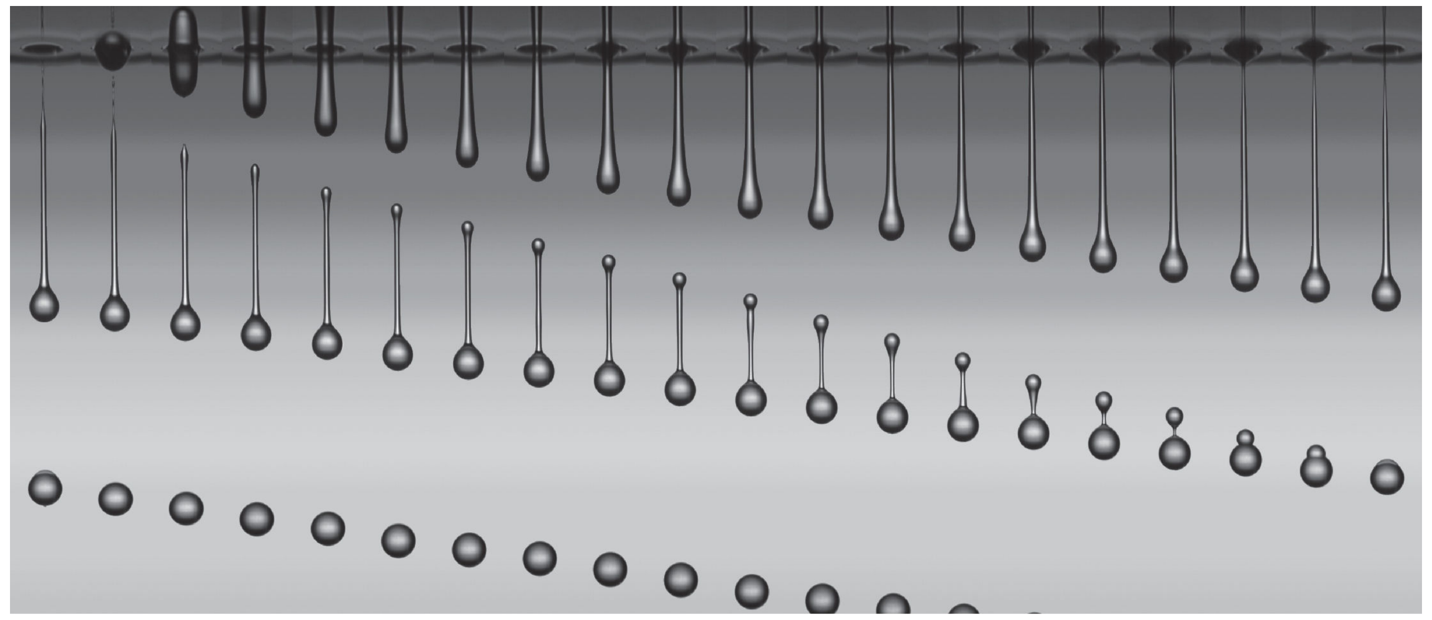
Oh vs We parameter space

Viscous Free-Surface Flows



Lohse, Annu. Rev. Fluid Mech. 2022. 54:349–82



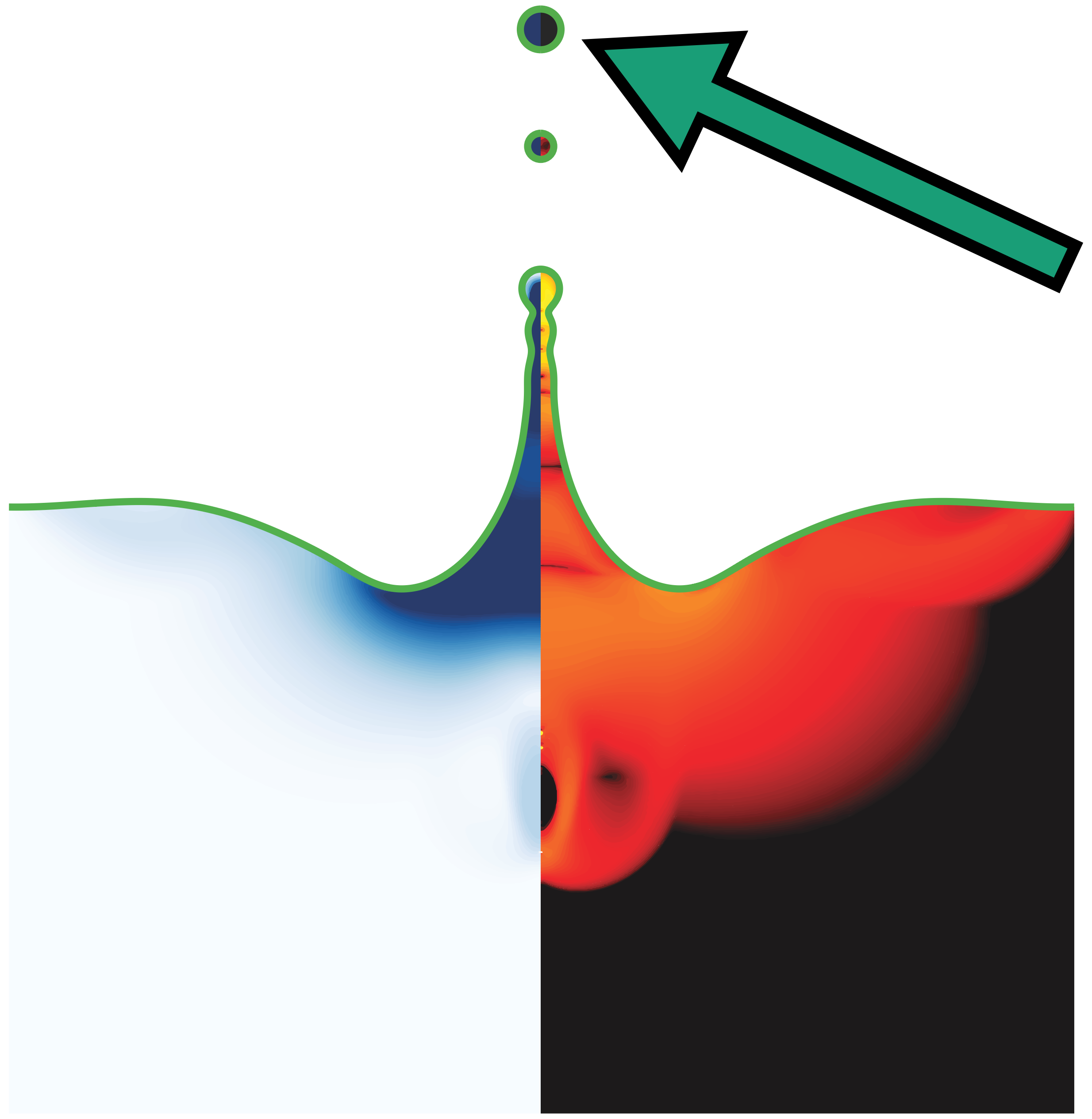


$$Oh = \frac{\eta_d}{\sqrt{\rho_d \gamma D_0}}$$

$$We = \frac{\rho_d V_0^2 D_0}{\gamma}$$

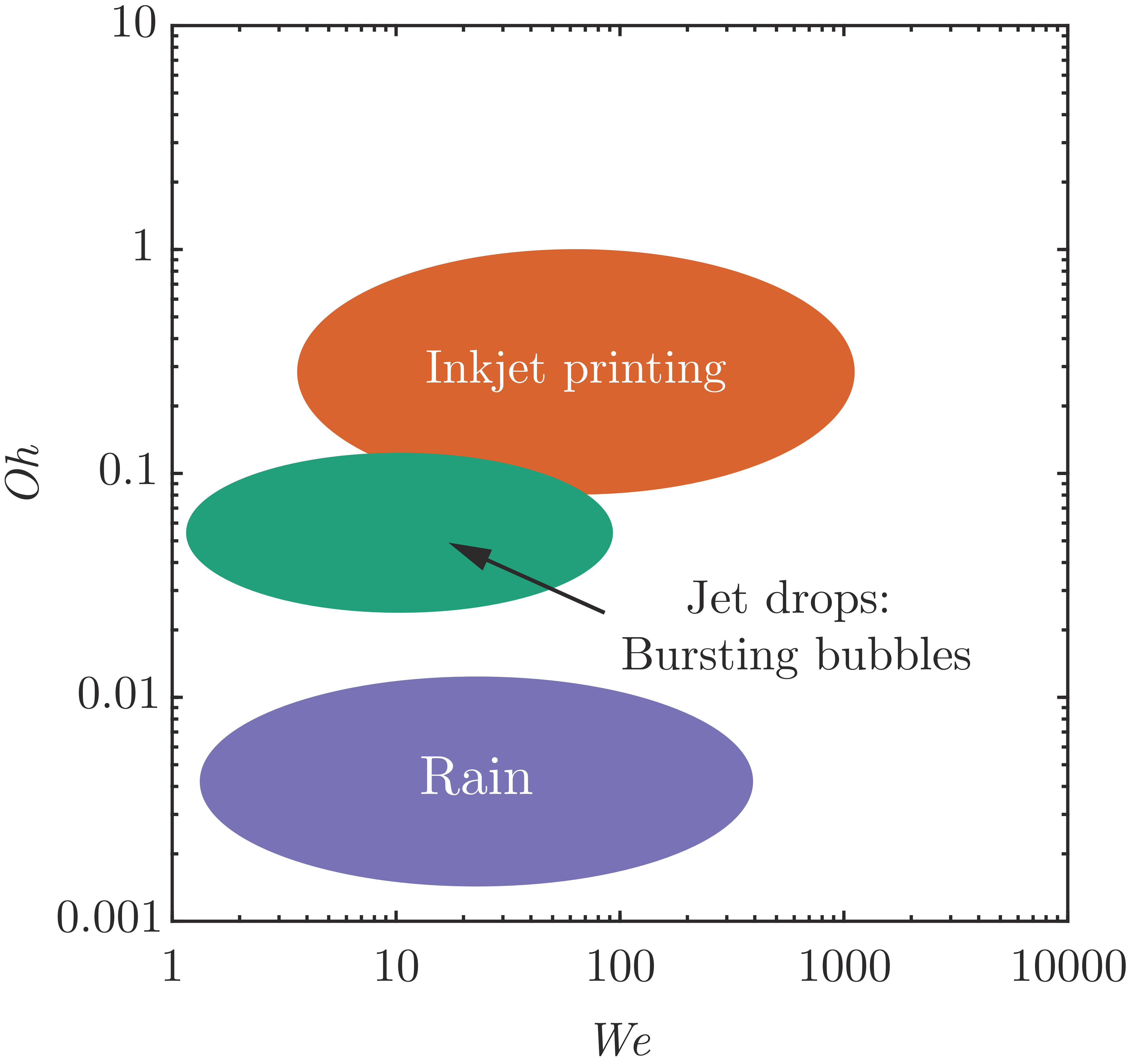
Oh vs We parameter space

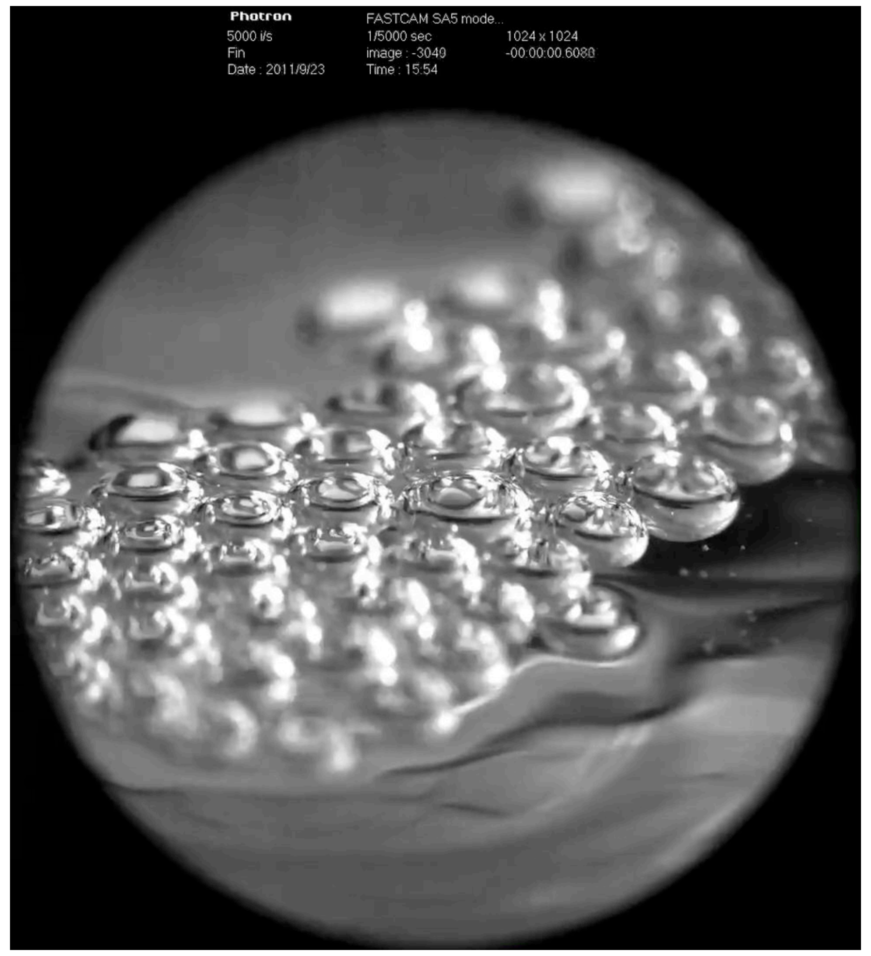
Viscous Free-Surface Flows



Sanjay, Lohse, & Jalaal,
J. Fluid Mech. (2021), vol. 922, A2

Néel & Deike,
Phys. Rev. Fluids **7**, 103603





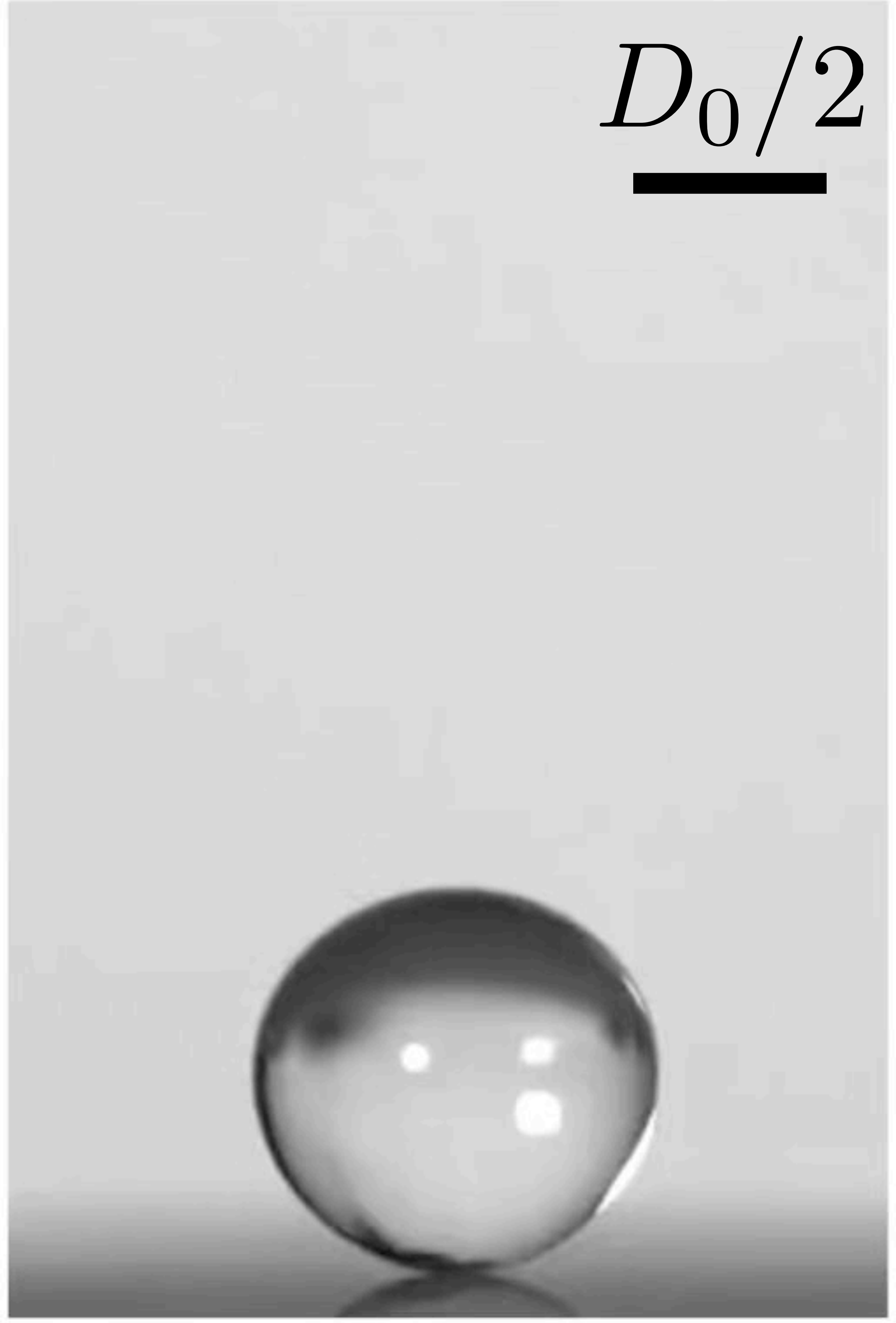
Video:
Thomas Séon & Arup Kumar Das

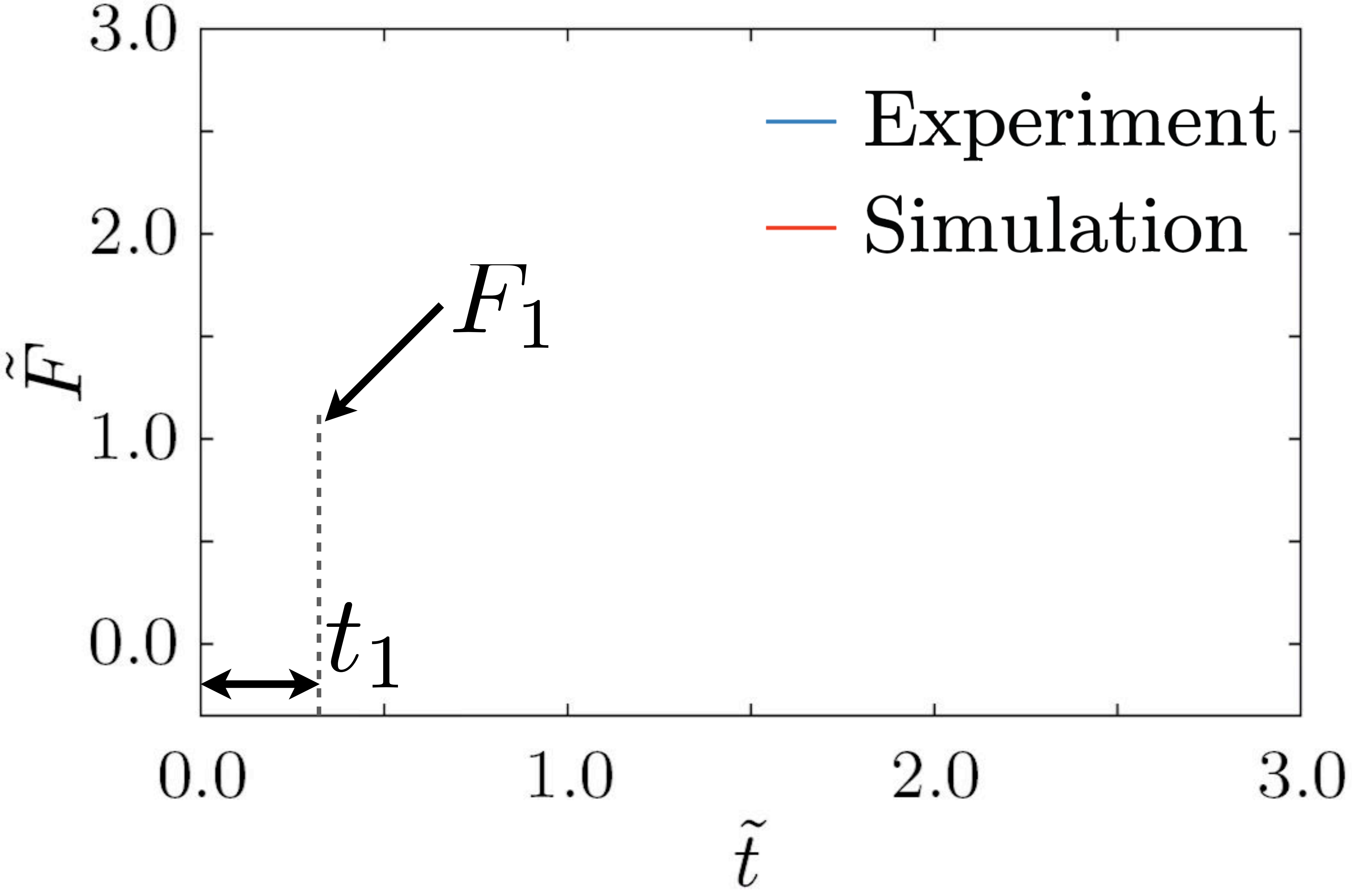
$$Oh = \frac{\eta_d}{\sqrt{\rho_d \gamma D_0}}$$

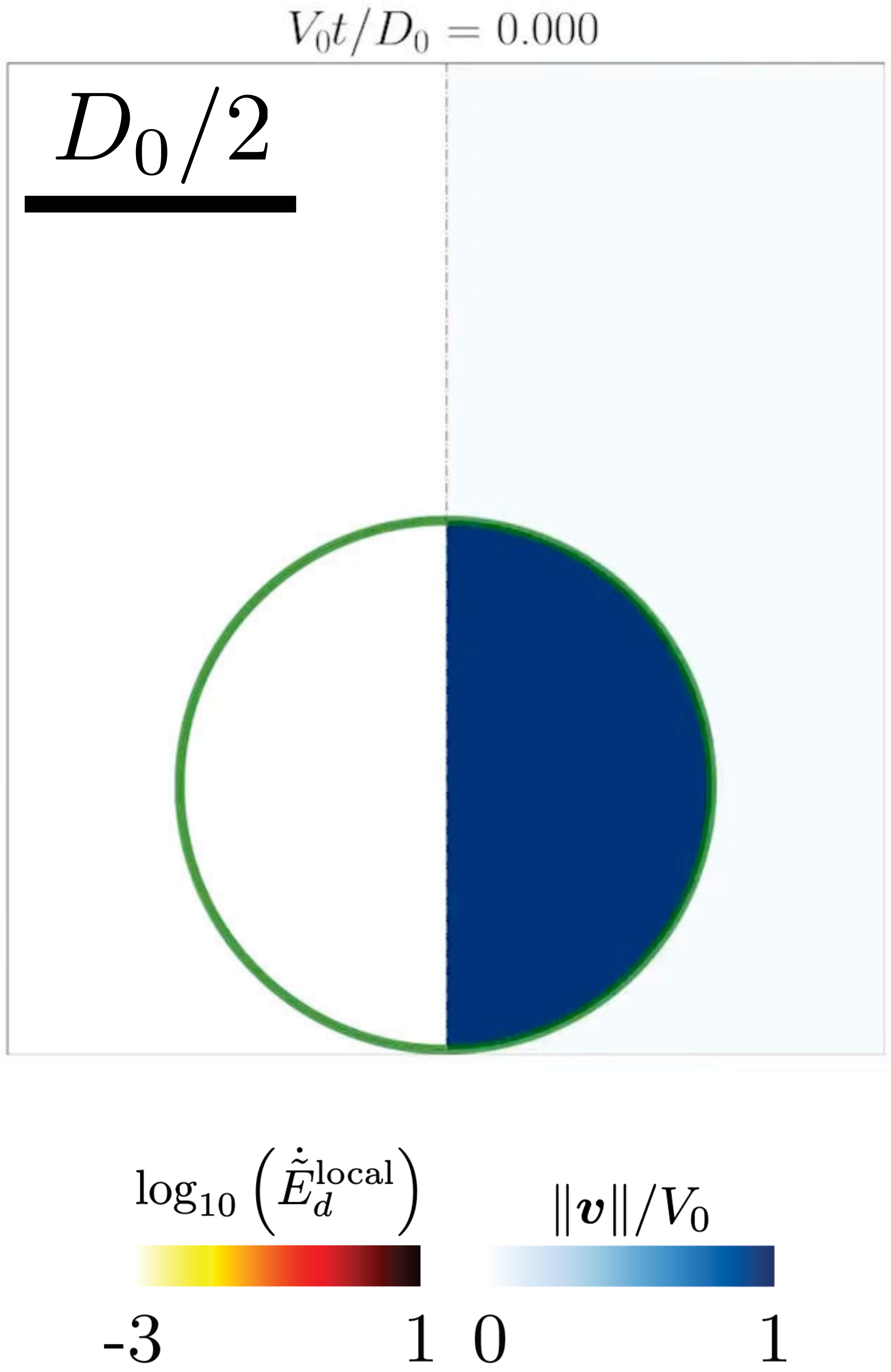
$$We = \frac{\rho_d V_0^2 D_0}{\gamma}$$

$We = 9$

$Oh = 0.0025$







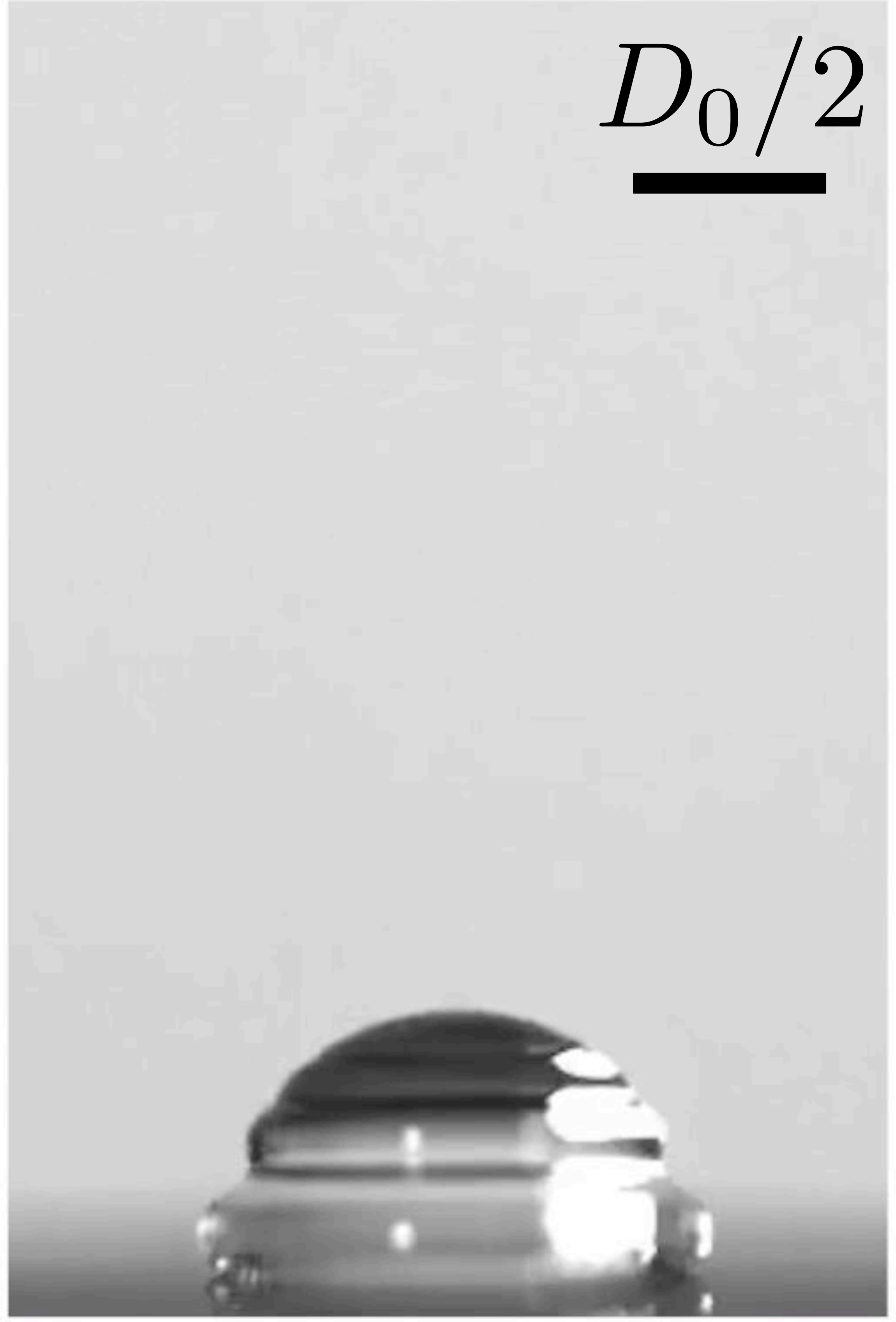
Phys. Rev. Lett. 129, 104501 (2022)

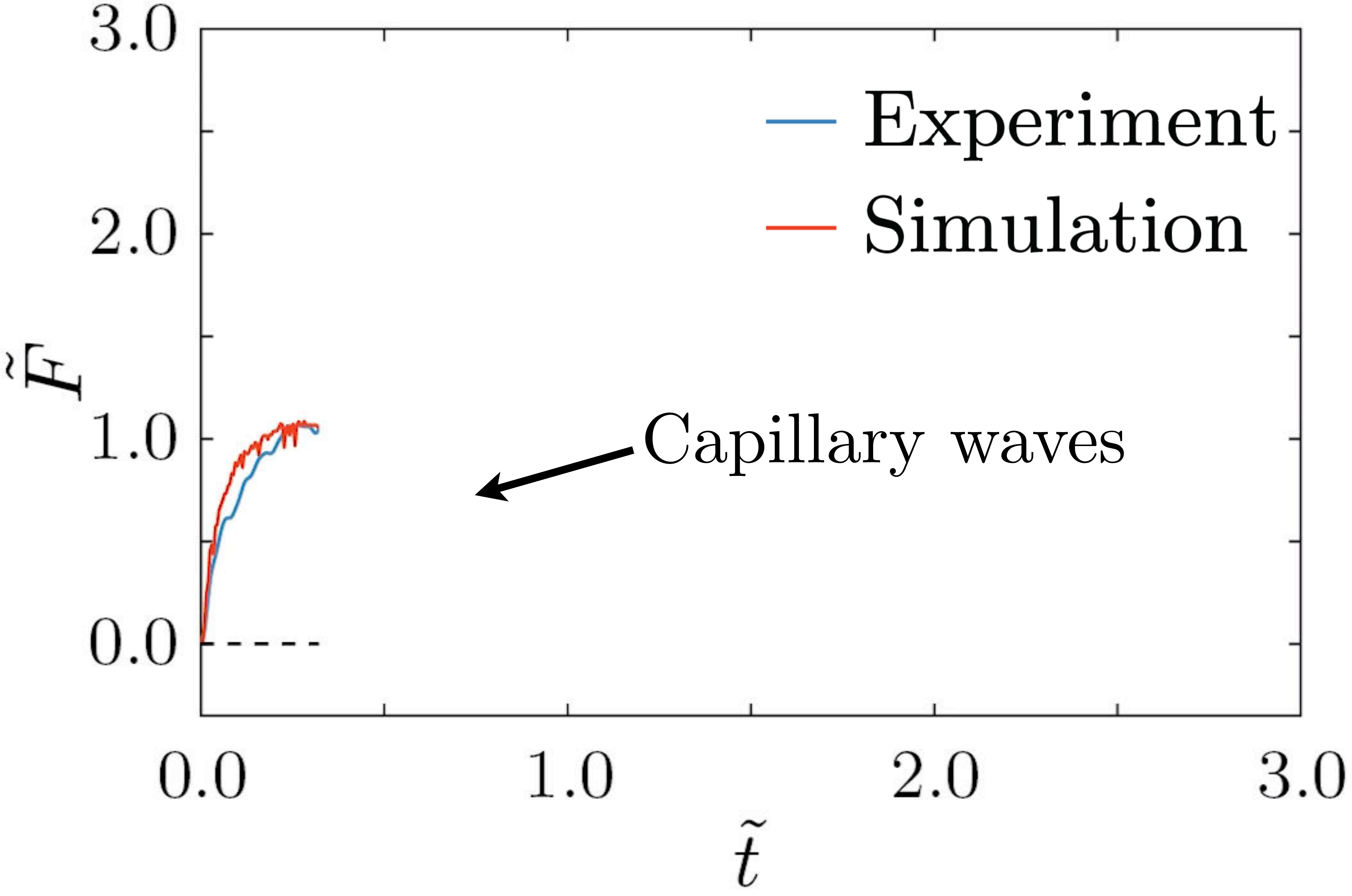
$$\dot{E}_d^{\mathrm{local}} = 2\eta\left(\boldsymbol{\mathcal{D}} : \boldsymbol{\mathcal{D}}\right)$$

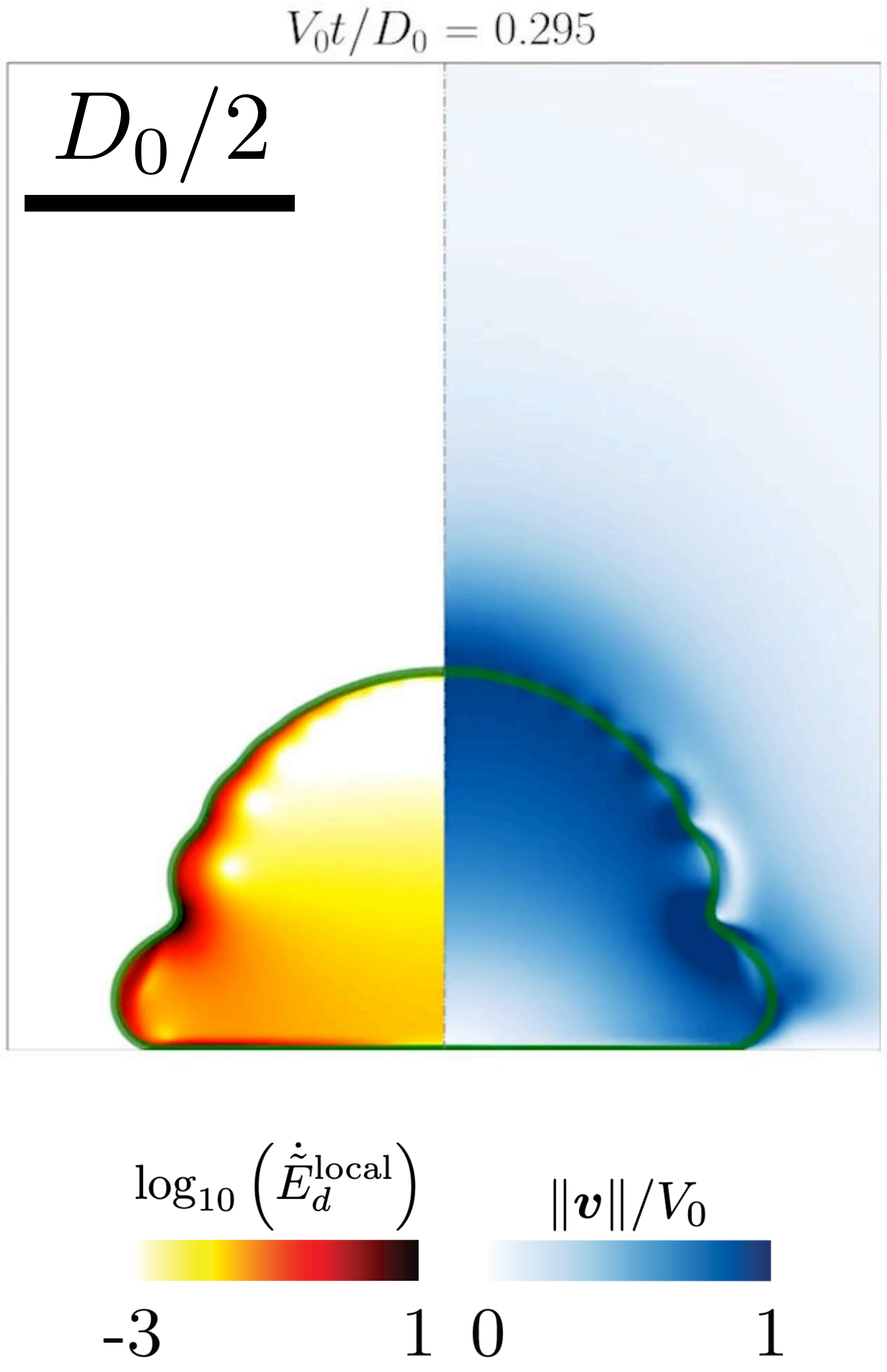
$$\boldsymbol{\mathcal{D}} = \left(\boldsymbol{\nabla v} + \left(\boldsymbol{\nabla v}\right)^{\mathrm{T}}\right)/2$$

$We = 9$

$Oh = 0.0025$





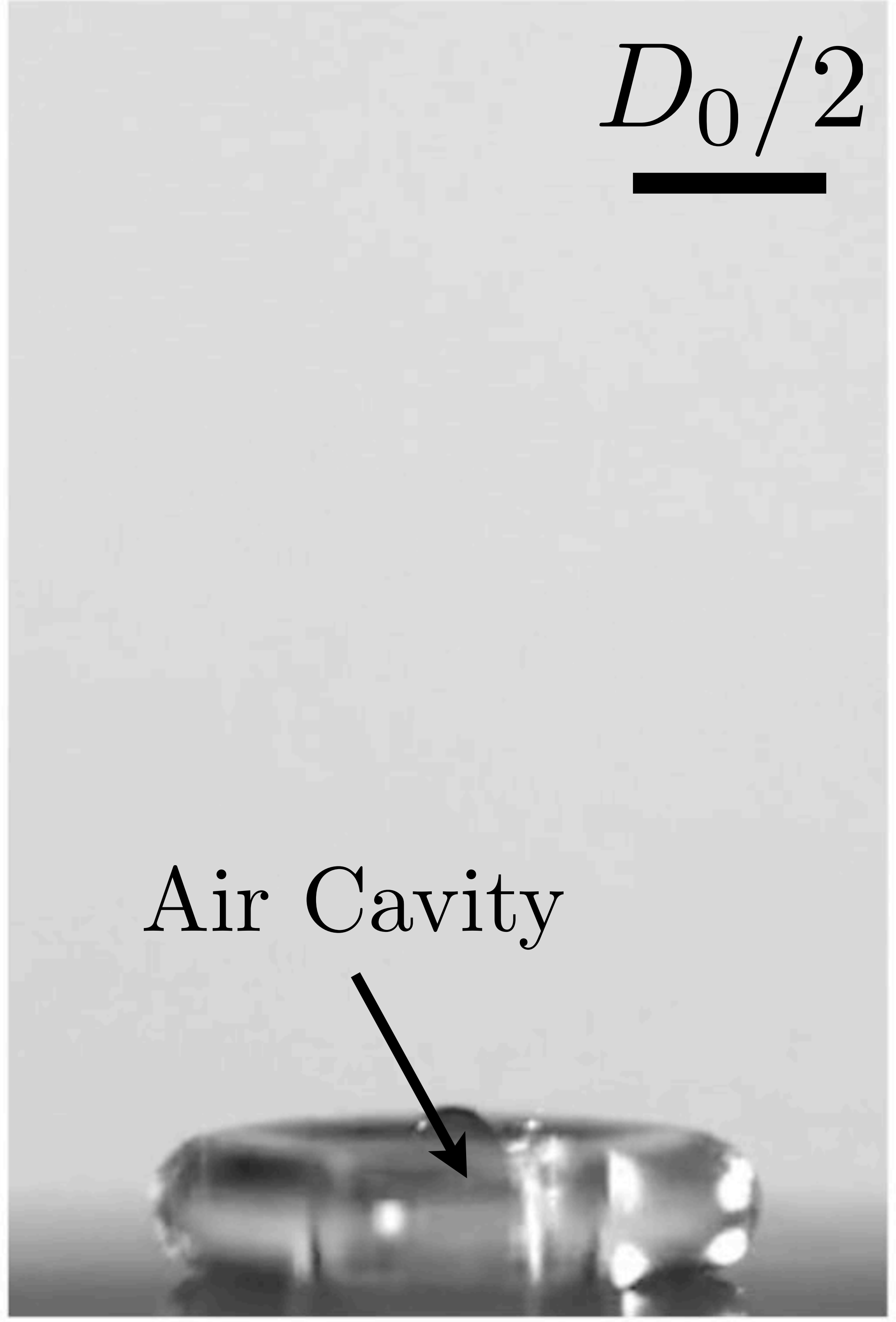


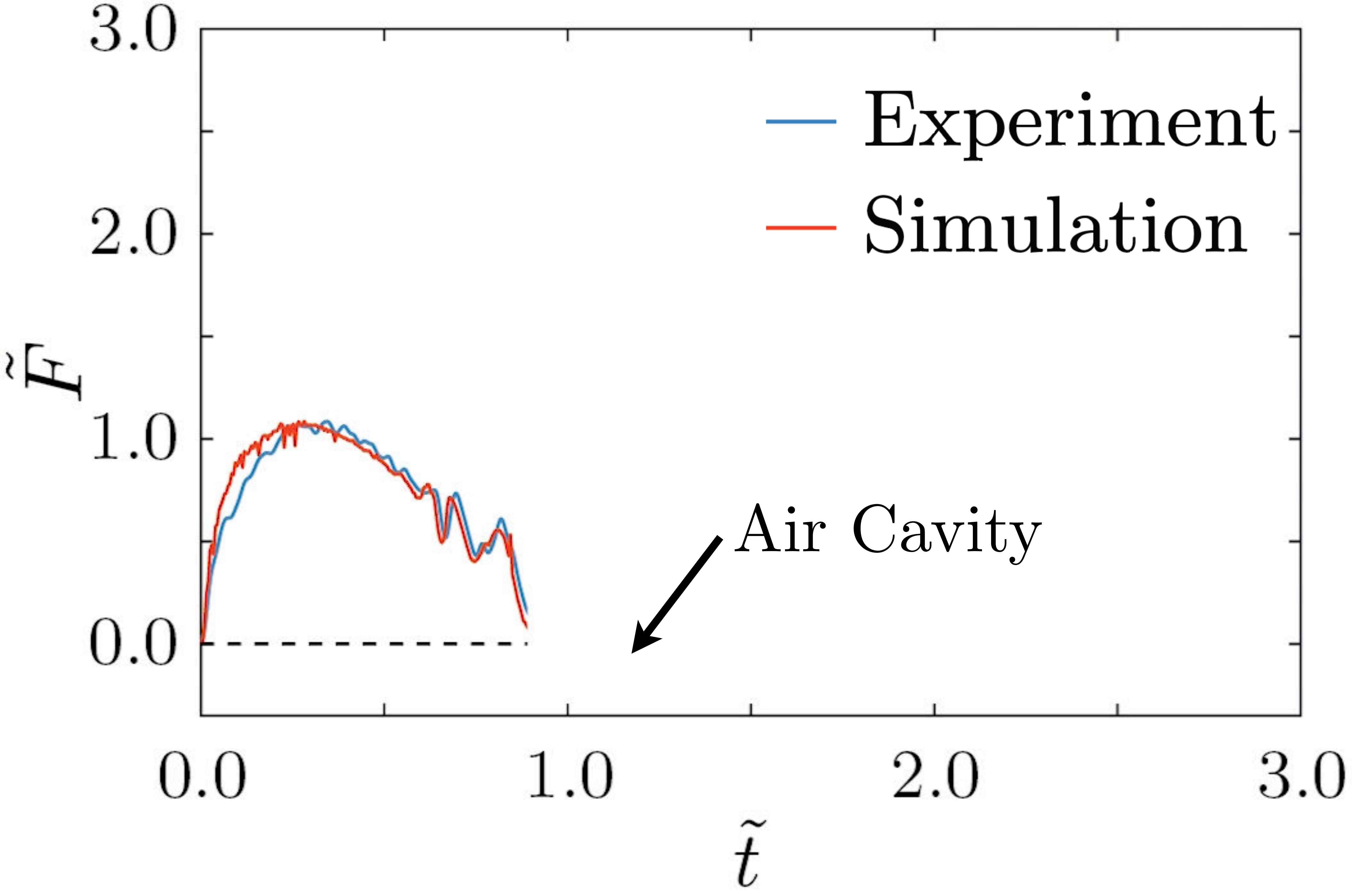
Phys. Rev. Lett. 129, 104501 (2022)

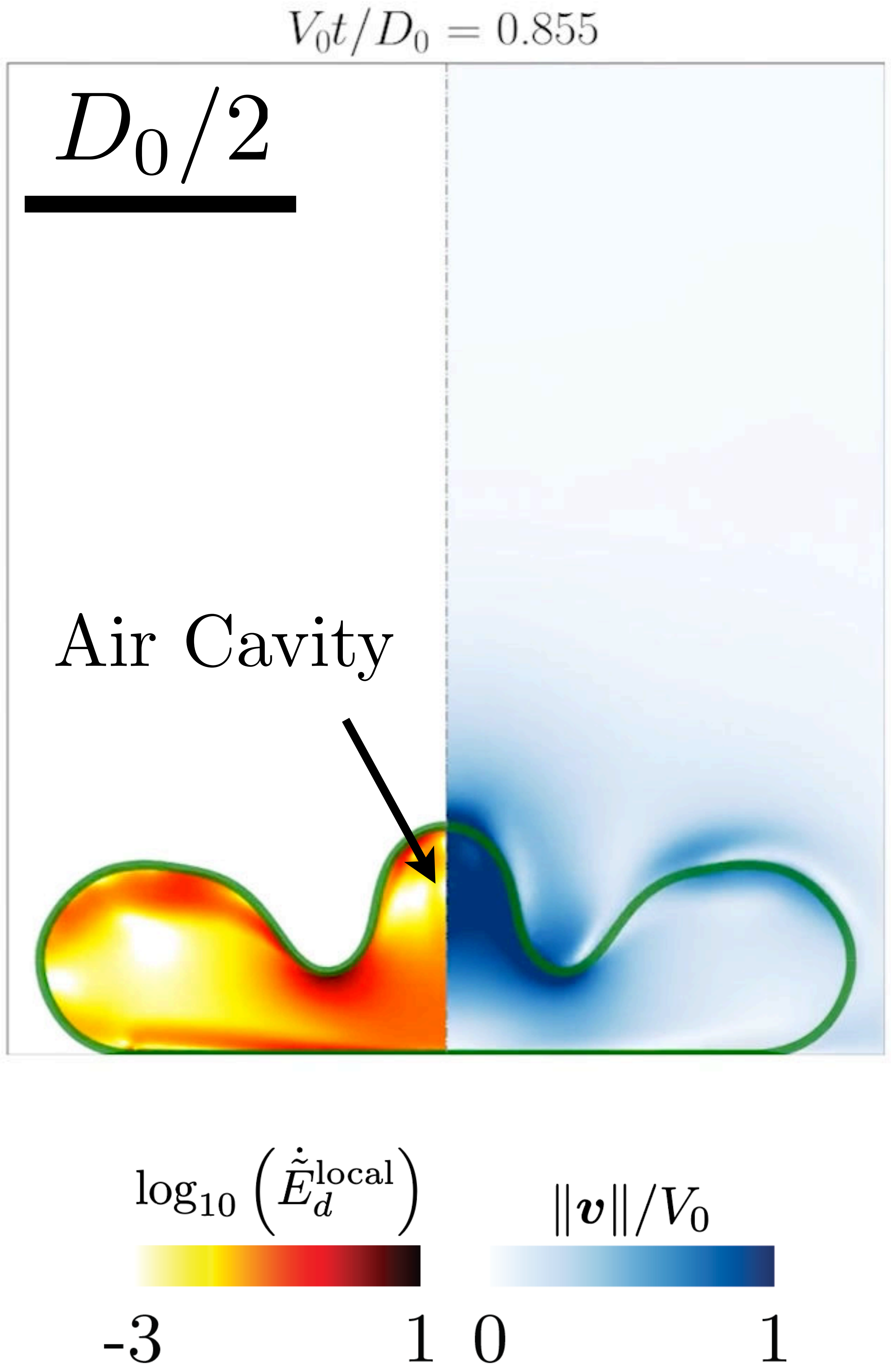
Renardy, **Popinet**, **Duchemin**, Renardy, **Zaleski**, **Josserand**,
Drumright-Clarke, Richard, Clanet, Quéré
J. Fluid Mech. 484, 69 (2003)

$We = 9$

$Oh = 0.0025$







Phys. Rev. Lett. 129, 104501 (2022)

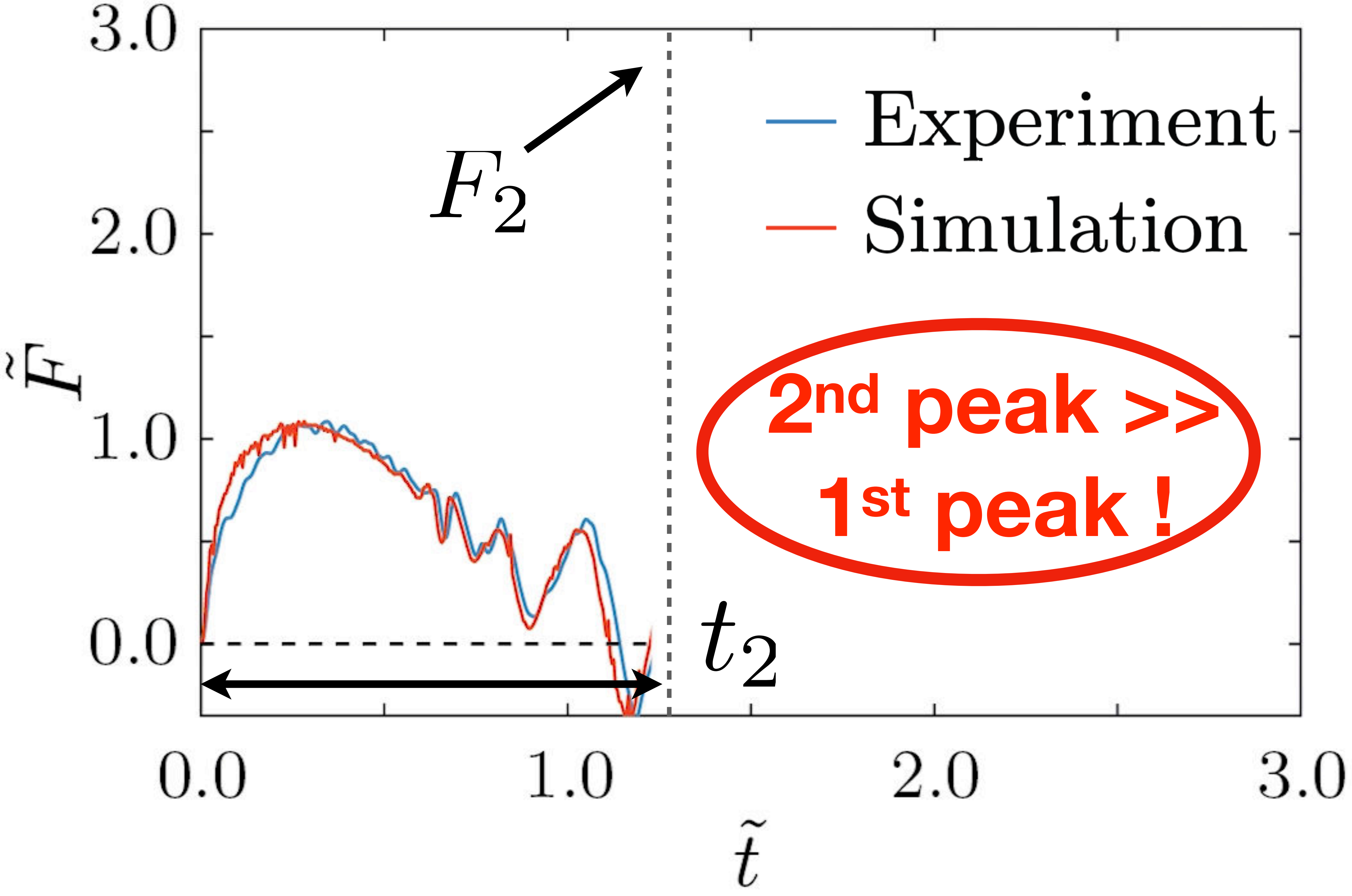
Air bubble entrainment !

Bartolo, **Josserand**, & Bonn

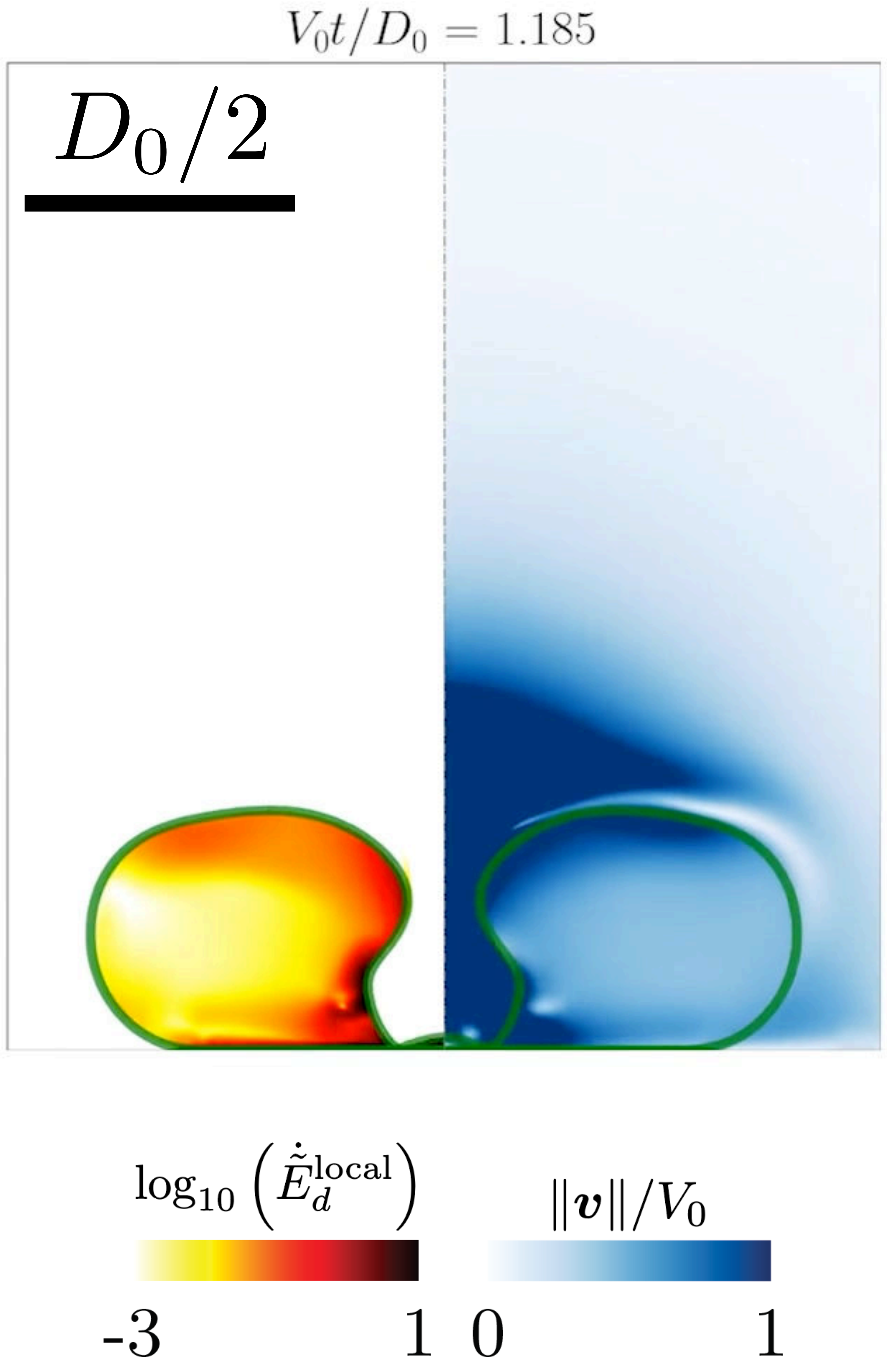
Phys. Rev. Lett. 96, 124501 (2006)

$We = 9$

$Oh = 0.0025$



2nd peak >> 1st peak !



Closure of air bubble leads to singular jet!

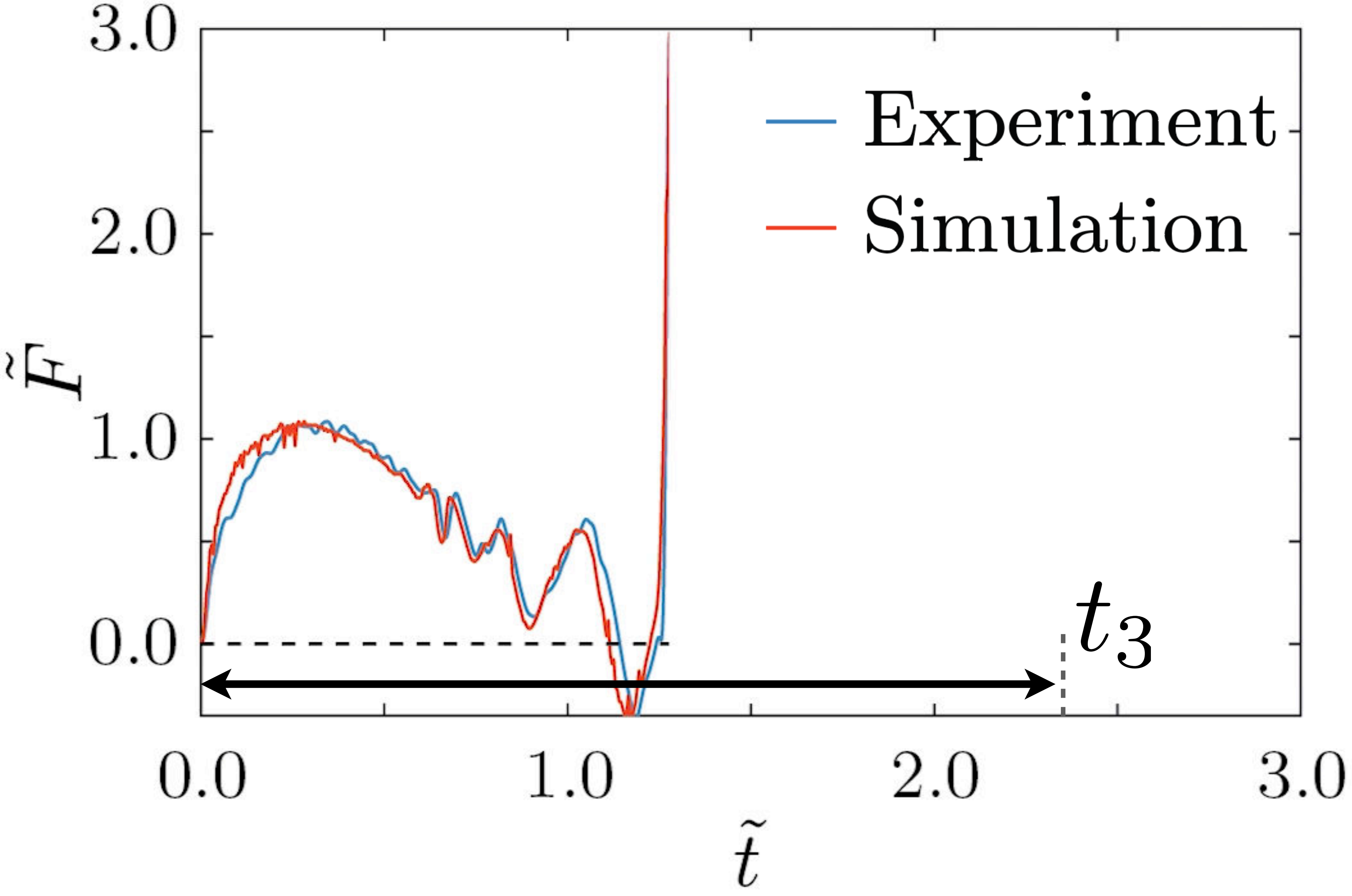
Bartolo, **Josserand**, & Bonn

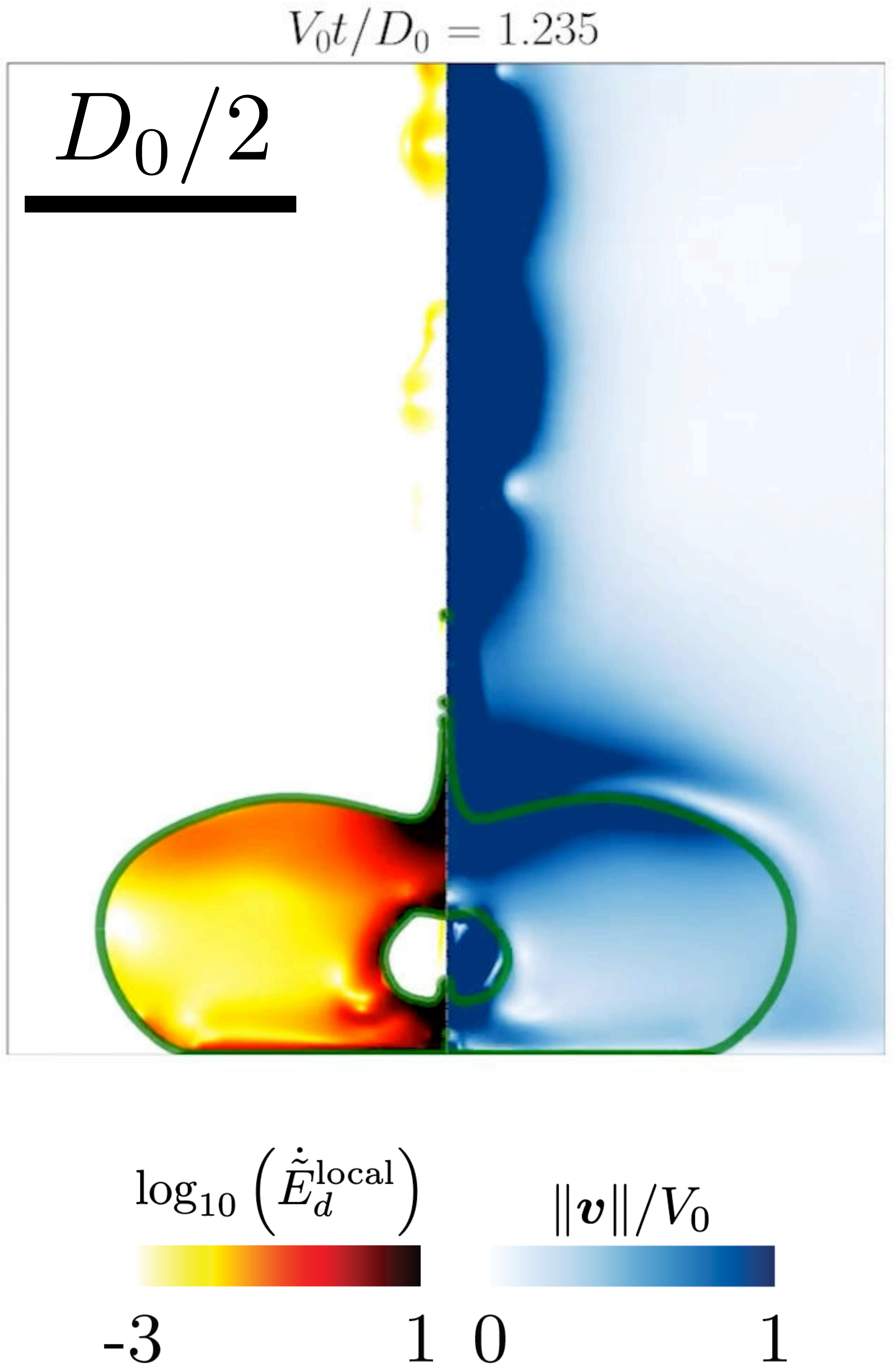
Phys. Rev. Lett. 96, 124501 (2006)

Phys. Rev. Lett. 129, 104501 (2022)

$We = 9$

$Oh = 0.0025$





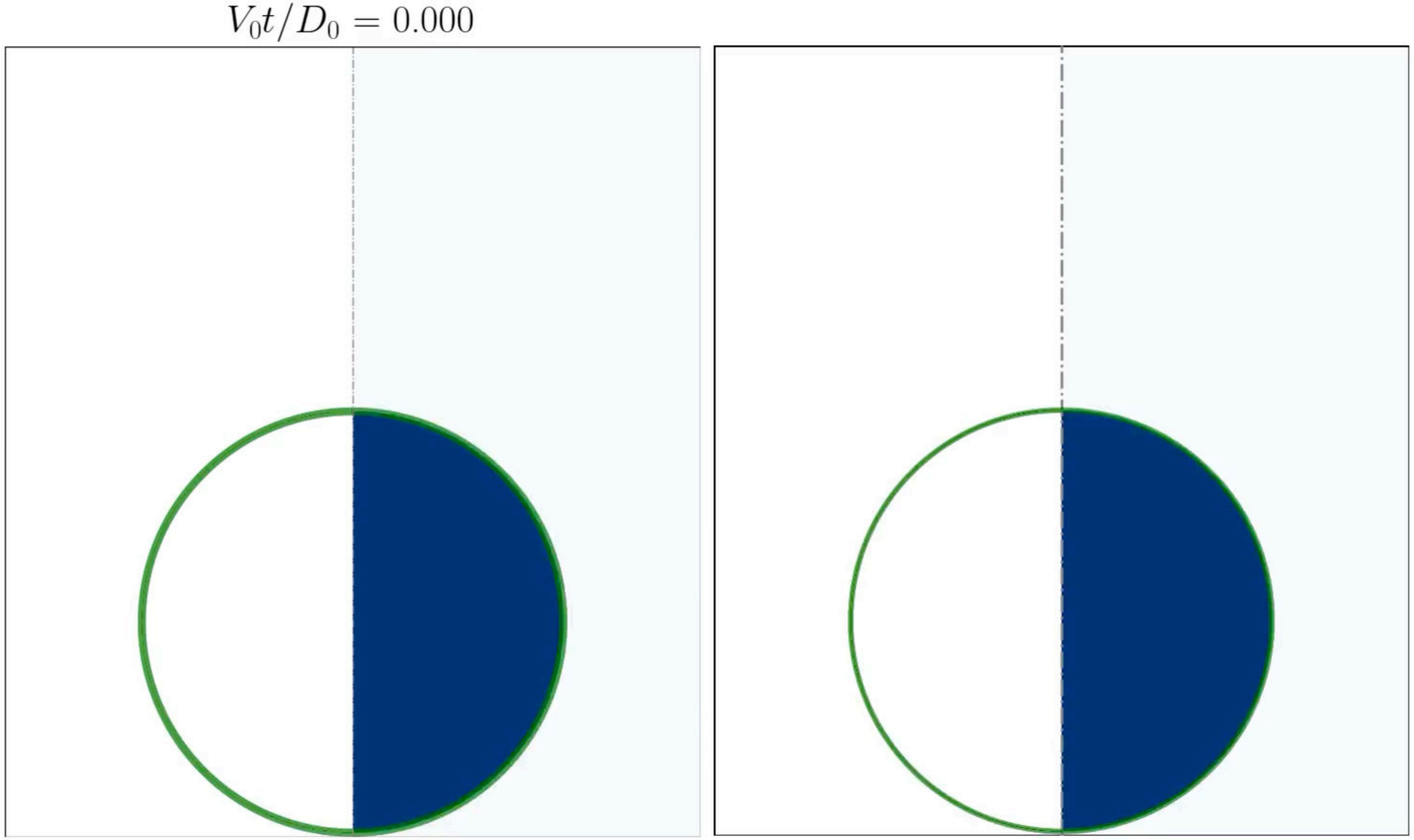
Phys. Rev. Lett. 129, 104501 (2022)

Ways to kill this ‘singularity’ !

I. Viscous dissipation

Jet & ~~bubble~~

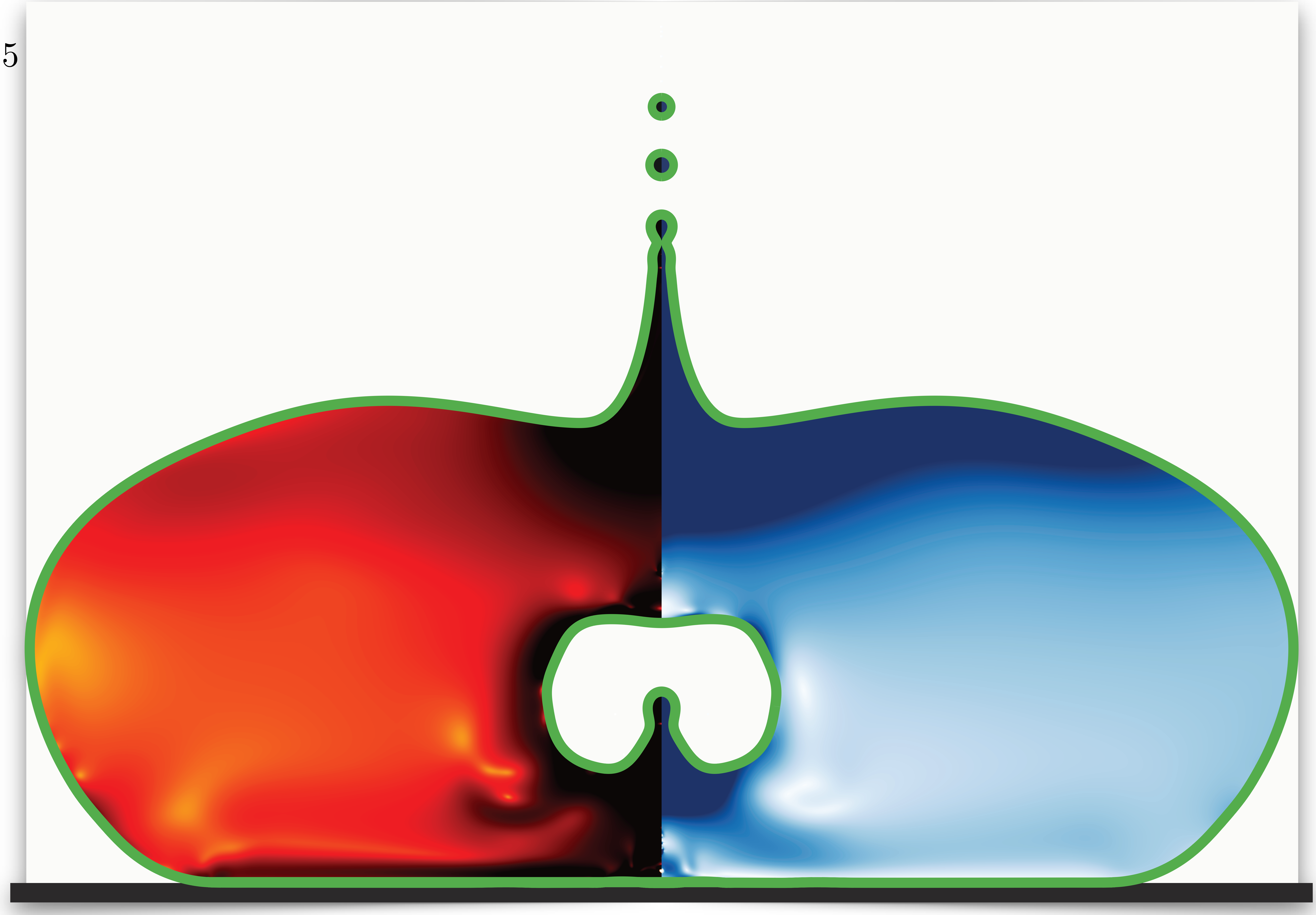
$We = 9$



$Oh = 0.0025$ $Oh = 0.005$

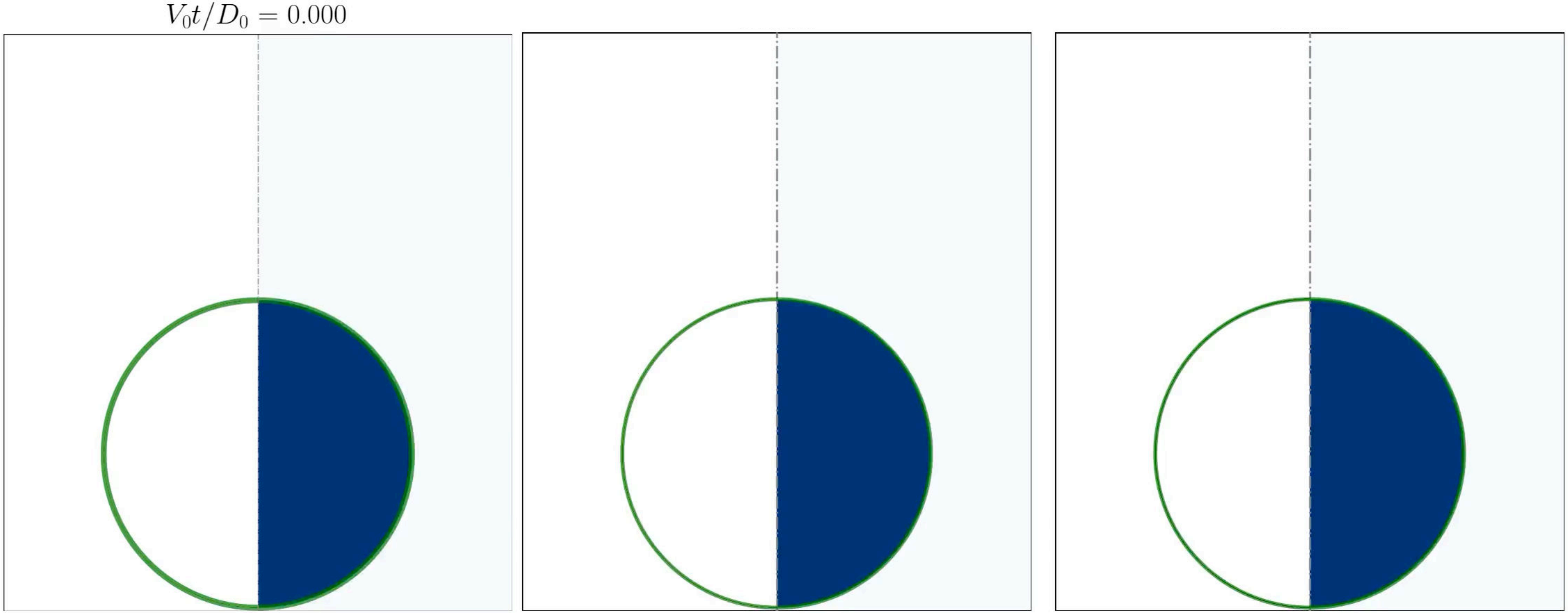
$We = 9$

$Oh = 0.0025$



Singular ~~jet~~ & ~~bubble~~

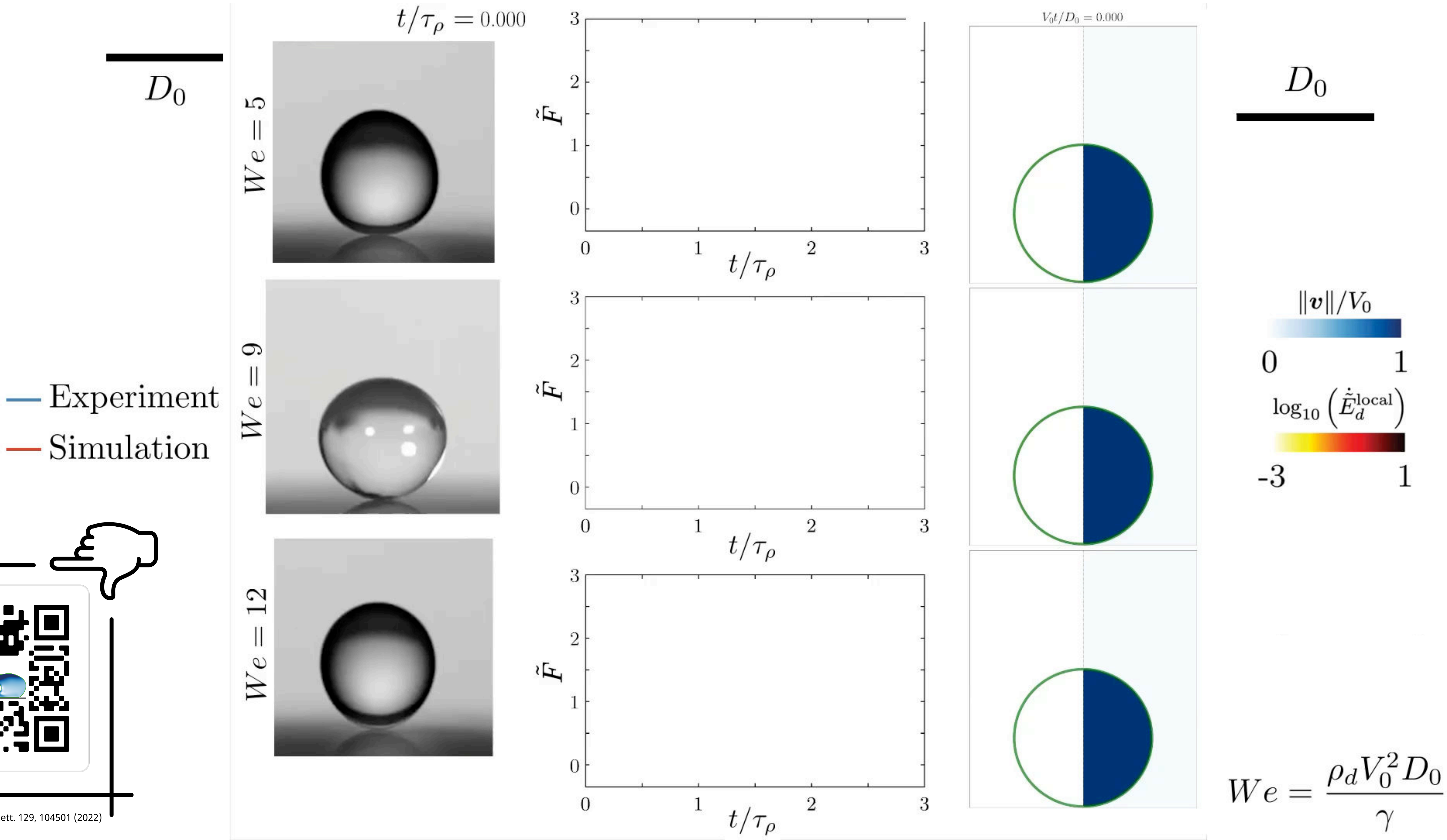
$We = 9$



$Oh = 0.0025$ $Oh = 0.005$ $Oh = 0.05$

II. What about the impact conditions?

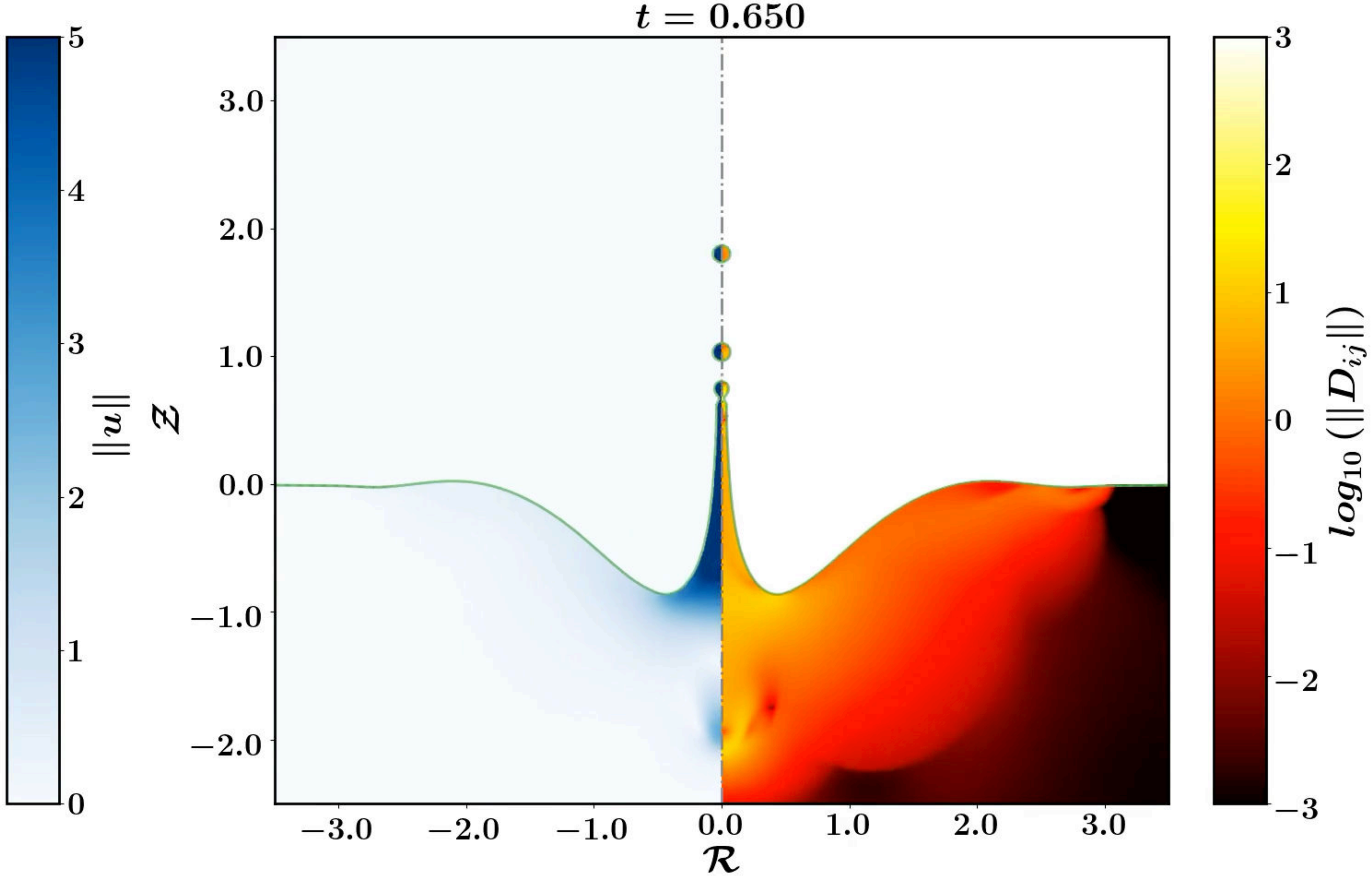
Bubble entrainment regime is very **narrow** $We \approx 9$



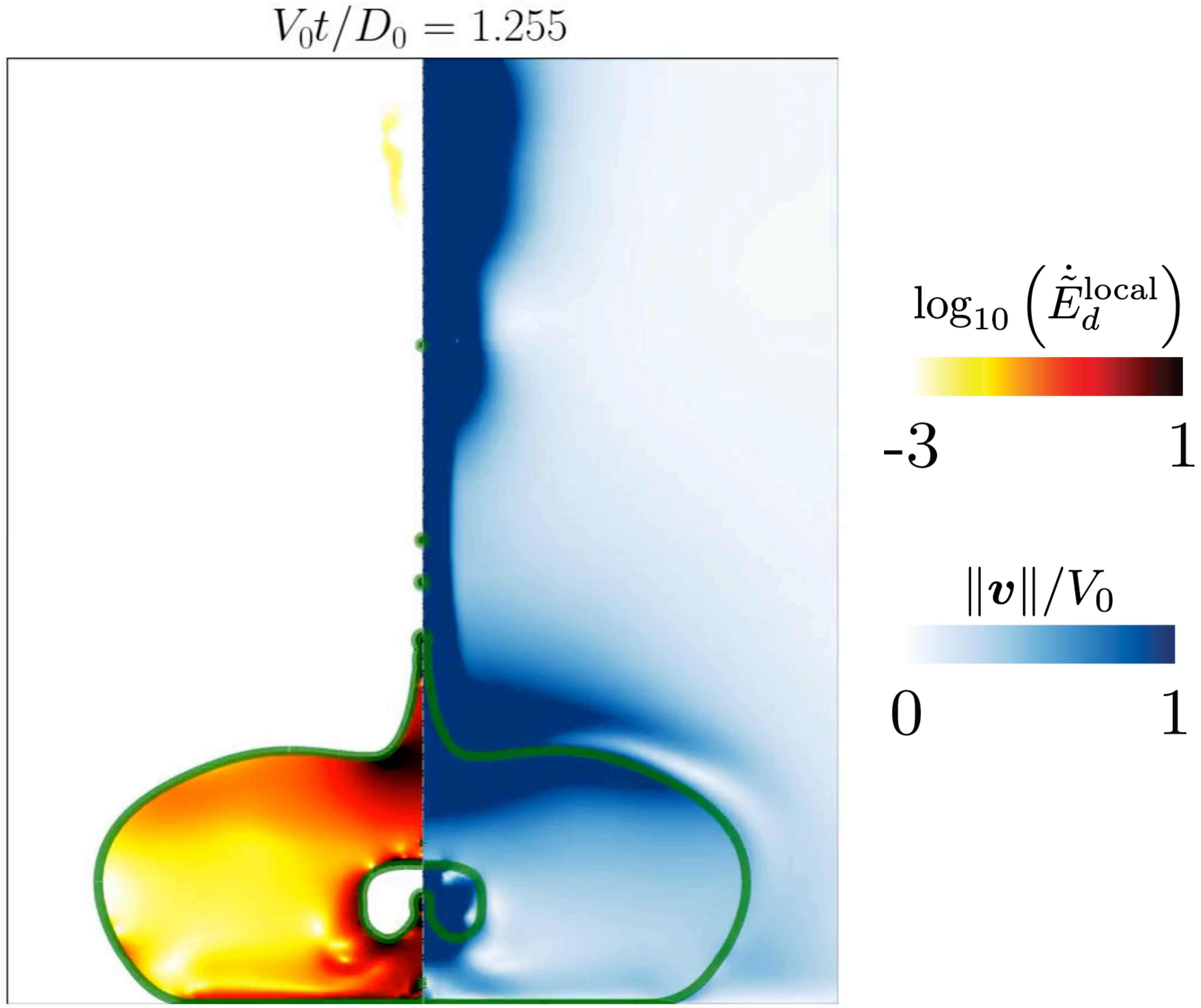
$$We = \frac{\rho_d V_0^2 D_0}{\gamma}$$

Phys. Rev. Lett. 129, 104501 (2022)

Throwback Friday: Worthington jets

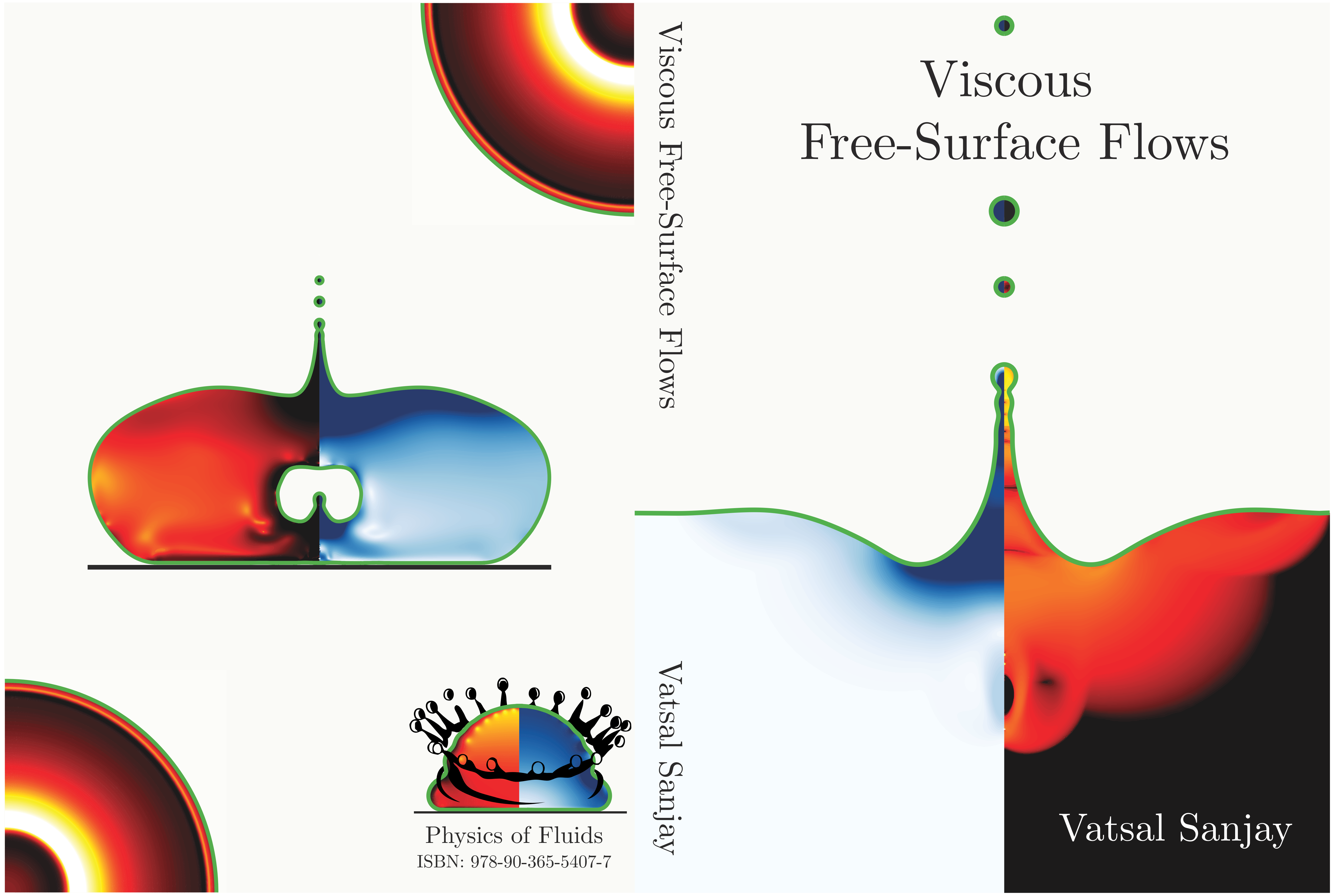


BGUM 2019



BGUM 2023

Worthington-type jets in the last 4 years



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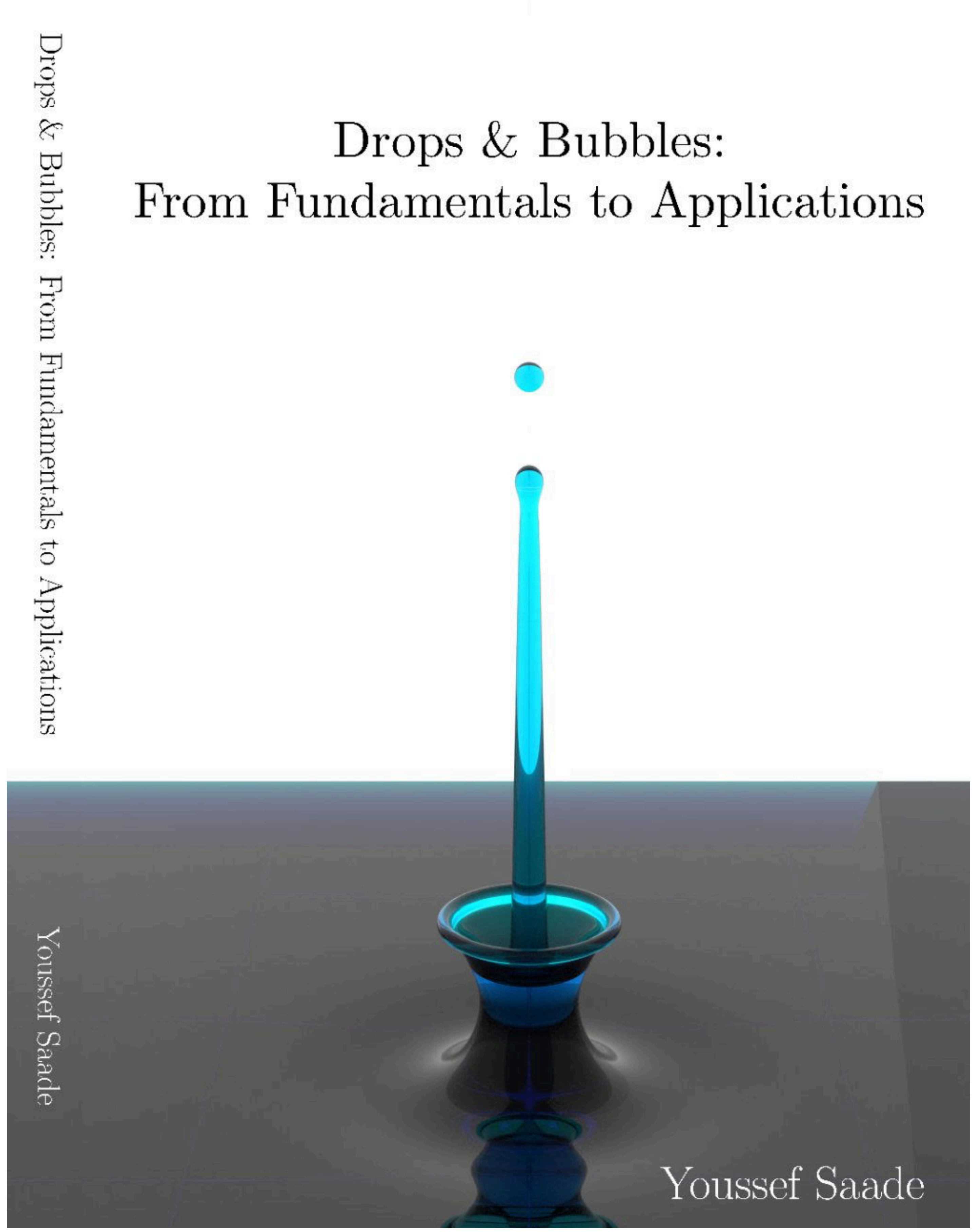
Vatsal Sanjay

Physics of Fluids
ISBN: 978-90-365-5407-7

Viscous
Free-Surface Flows

Vatsal Sanjay



Drops & Bubbles: From Fundamentals to Applications

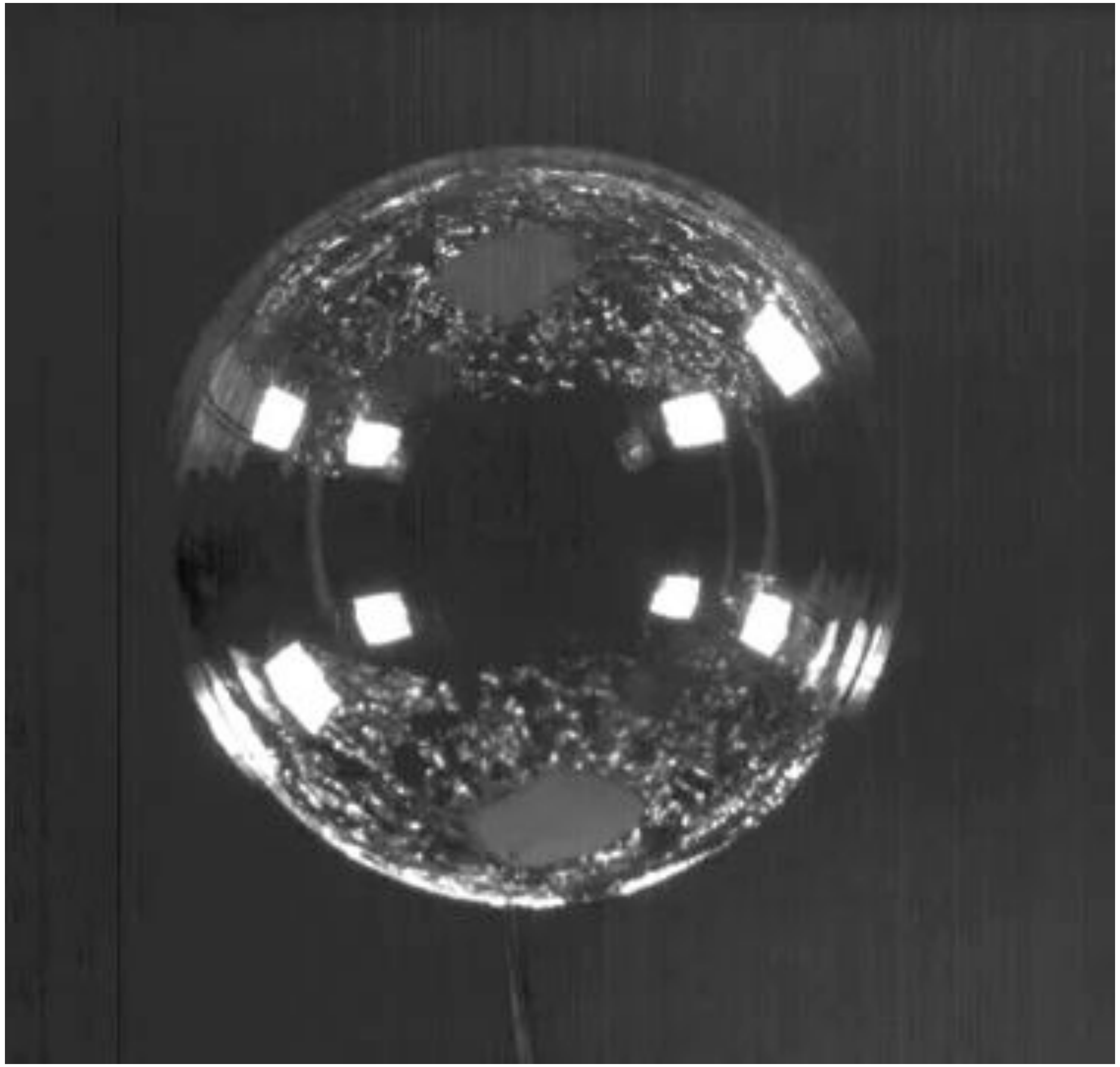
Youssef Saade

Drops & Bubbles:
From Fundamentals to Applications

Youssef Saade

More free-surface flows

(Another) Real life examples



Video from https://fyfluiddynamics.com/2011/10/high-speed-video-of-a-soap-bubble-being-popped/

Taylor-Culick Retractions


Detlef Lohse


Udo Sen

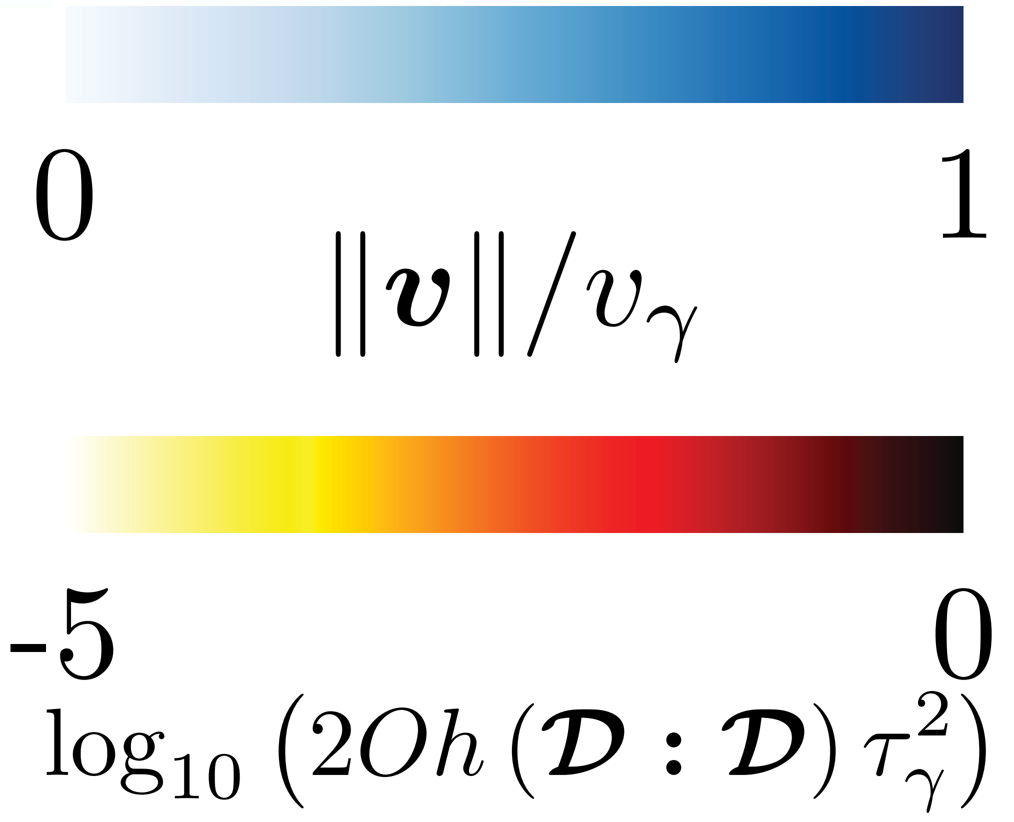

Pallav Kant

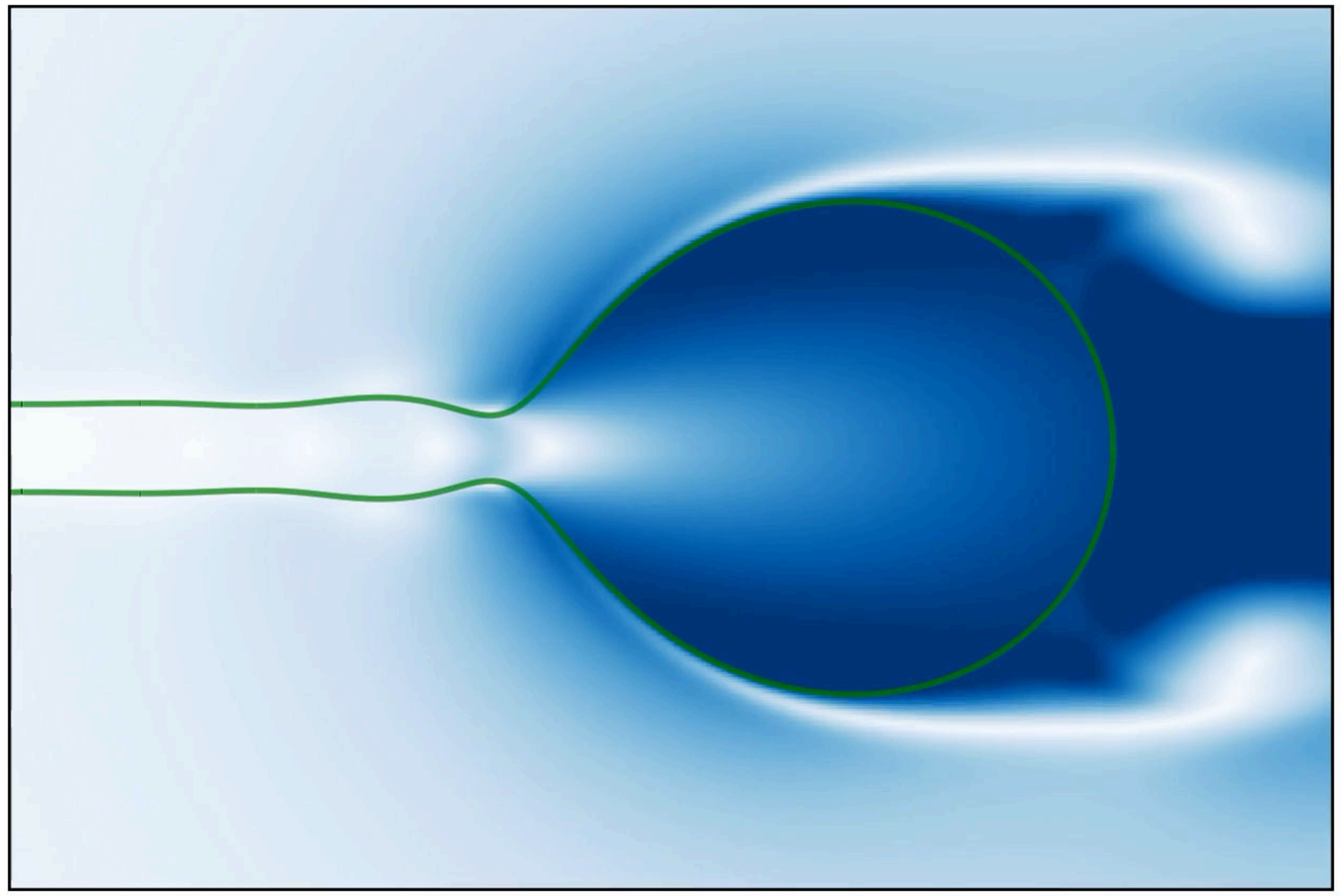
Classical Taylor-Culick retraction

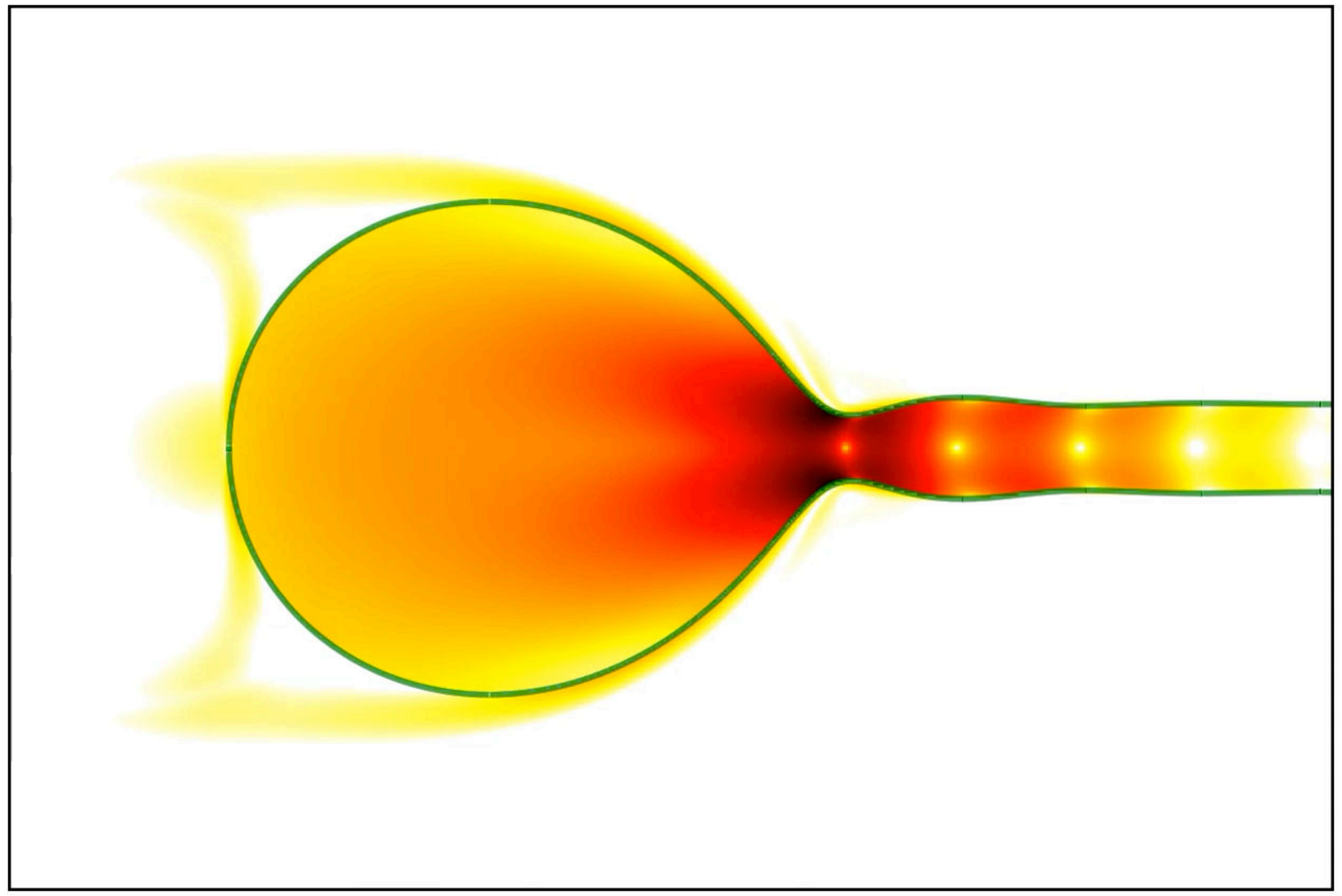
$$Oh_f = 0.05$$

$$Oh = \frac{\eta}{\sqrt{\rho_f (2\gamma_{af}) h_0}}$$

$$t/\tau_\gamma = 50.500$$



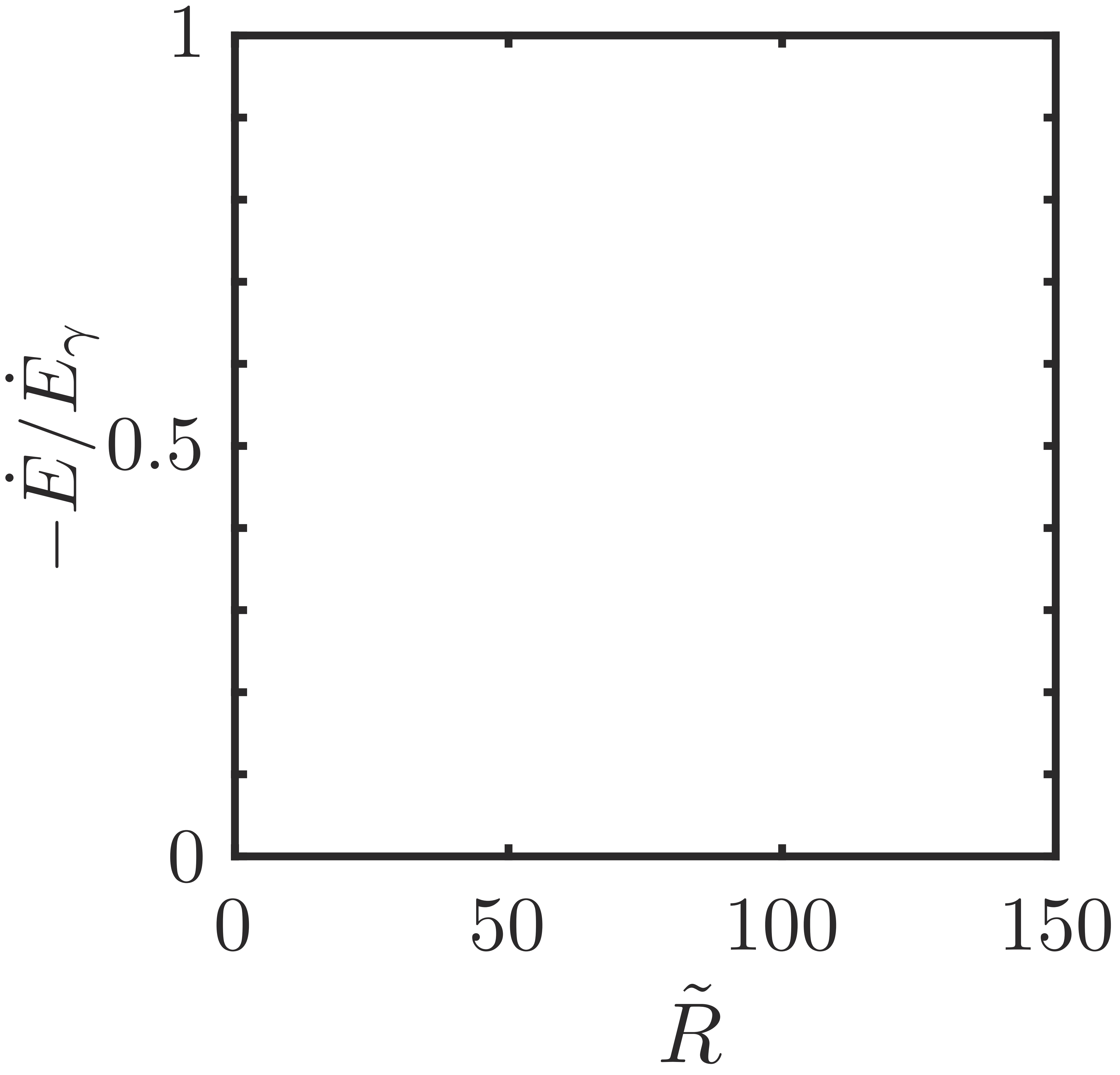


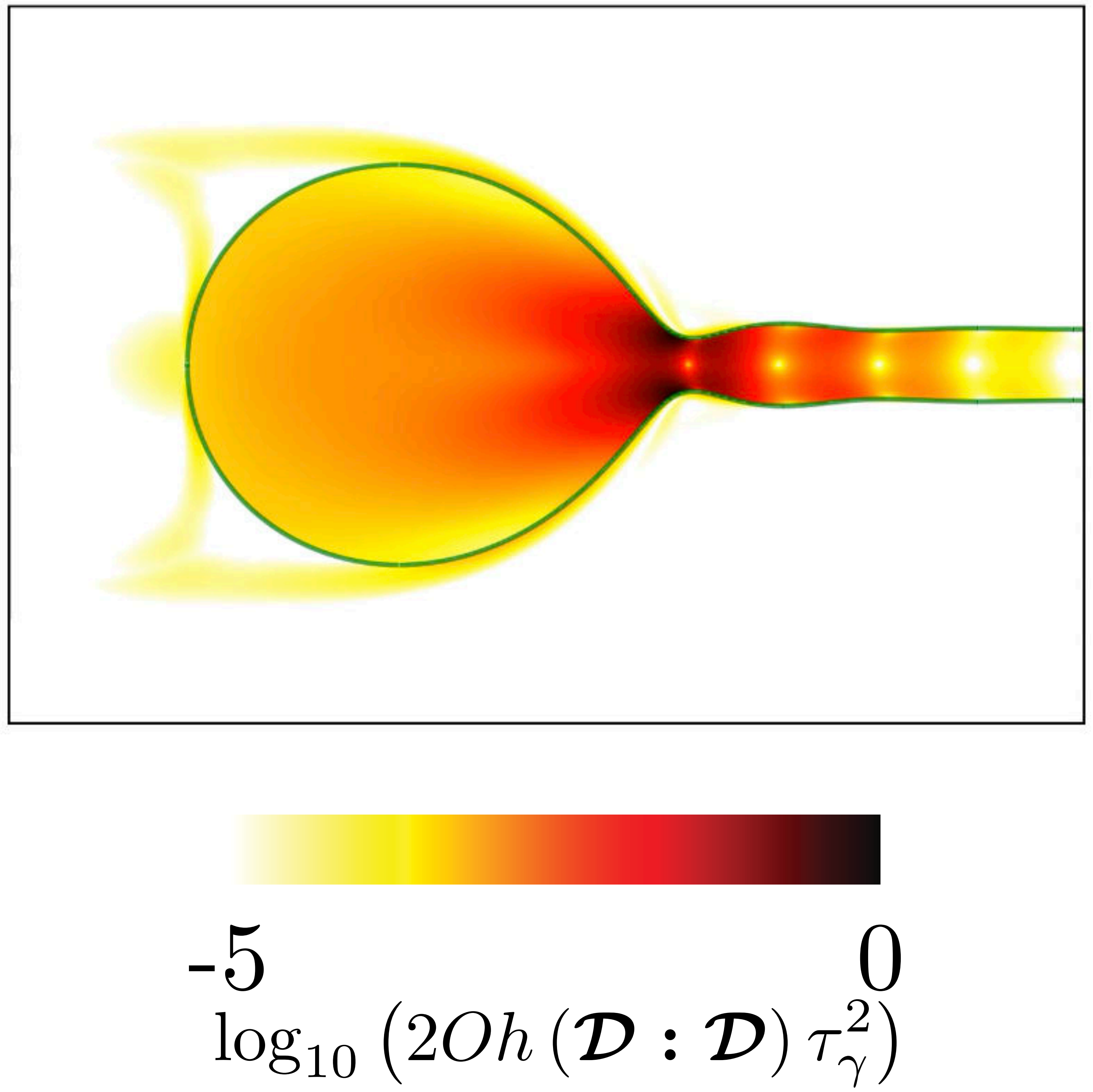


$$\boldsymbol{\mathcal{D}} = \left(\boldsymbol{\nabla v} + (\boldsymbol{\nabla v})^{\mathrm{T}}\right)/2$$

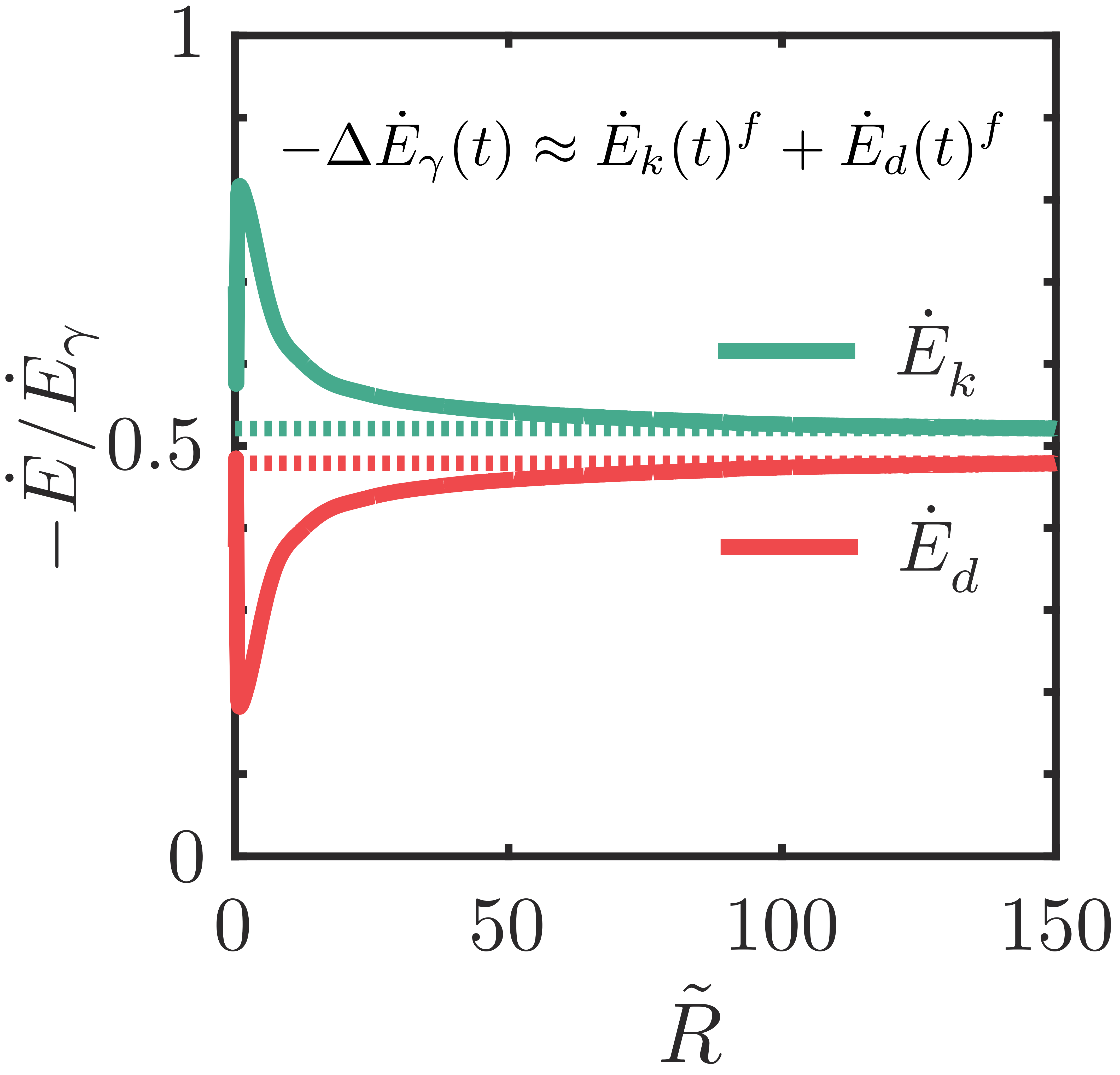
$$\tau_\gamma = \sqrt{\frac{\rho_f h_0^3}{2\gamma_{af}}} \quad v_\gamma = \sqrt{\frac{2\gamma_{af}}{\rho_f h_0}}$$

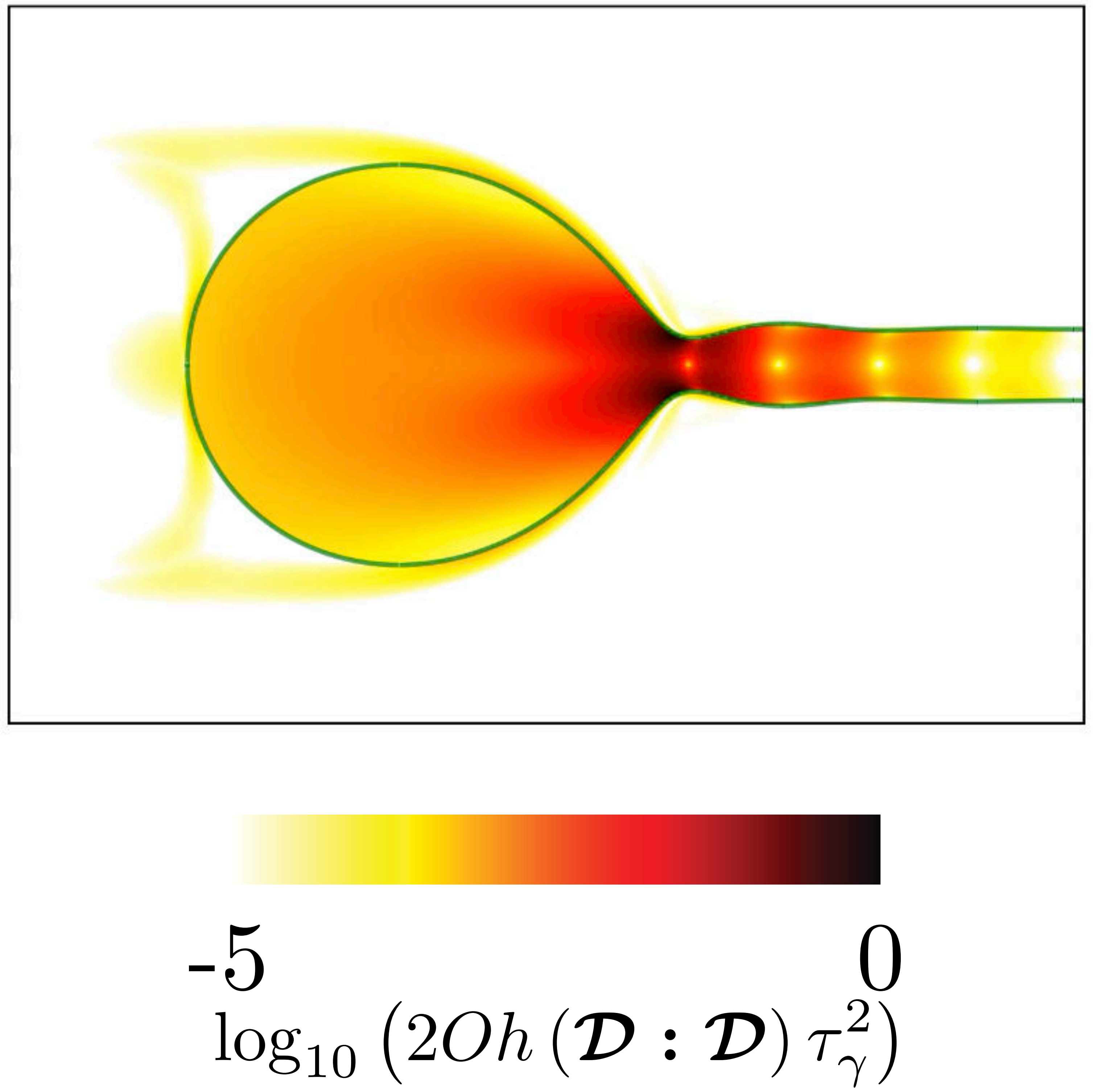
Energy Budget: Classical Taylor-Culick retraction





Energy Budget: Classical Taylor-Culick retraction

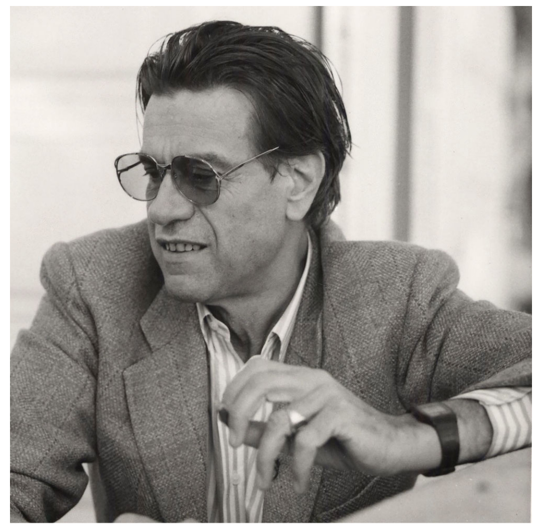




$$\dot{E}_d = \frac{1}{2}\frac{dm}{dt}v^2$$

G. I. Taylor

F. E. C. Culick



P.-G. de Gennes

Synopsis of **Classical** Taylor-Culick retractions

$$v_f = v_{TC} = \sqrt{\frac{(2\gamma_{fa})}{\rho_f h_0}}$$

- Even in the inertial limit, cannot neglect viscous dissipation in the thin film

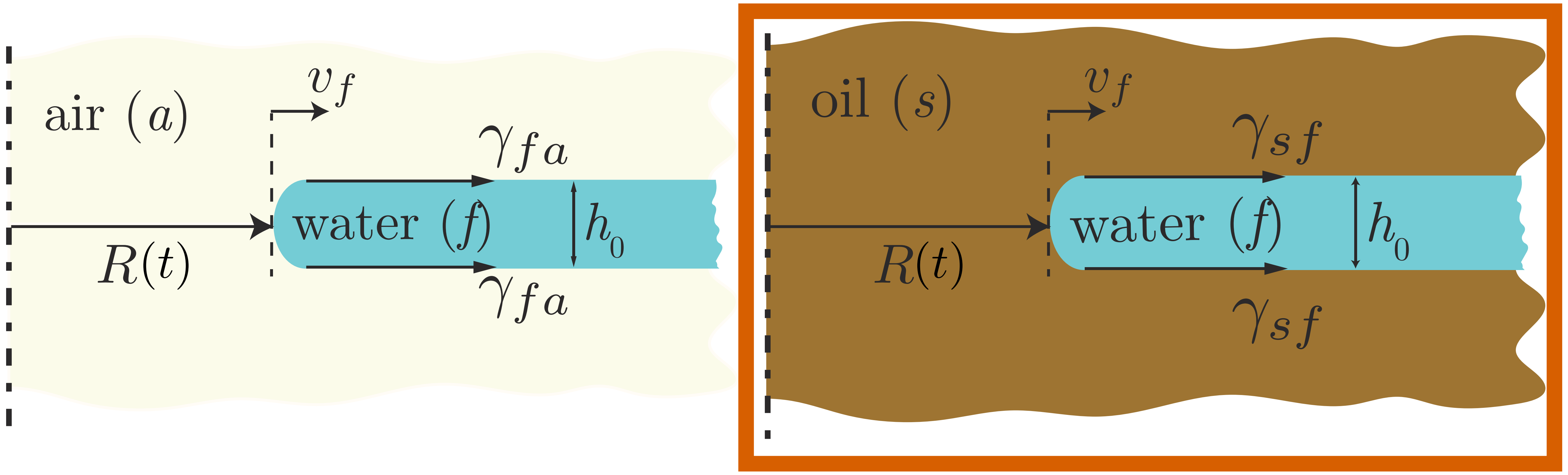
$$-\Delta\dot{E}_\gamma(t) \approx \dot{E}_k(t)^f + \dot{E}_d(t)^f$$

- Dissipation is independent of viscosity.

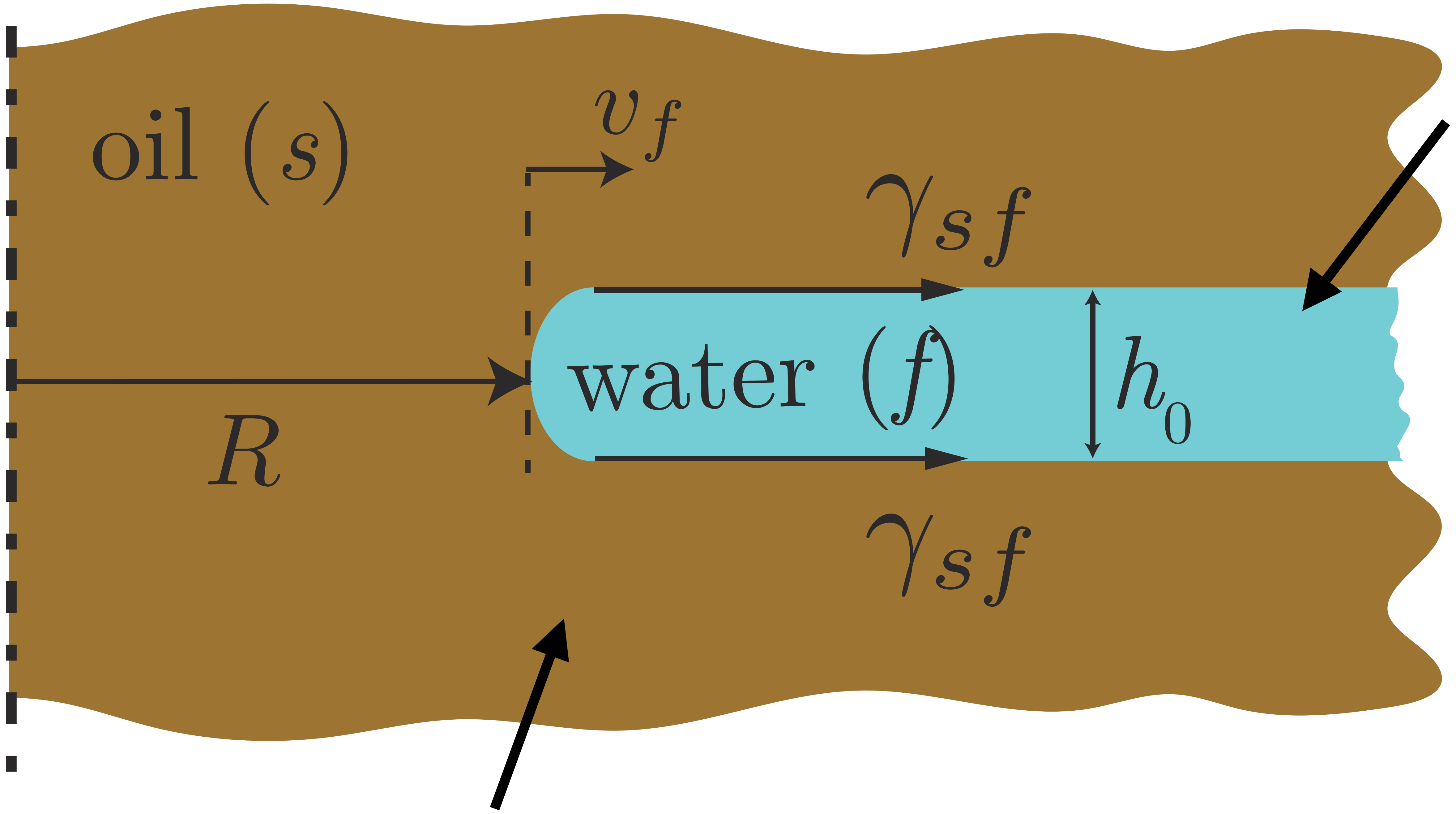
$$\dot{E}_d = \frac{1}{2}\frac{dm}{dt}v^2$$

Beyond the free-surface ...

What happens if the surrounding medium is not air?



Problem Statement



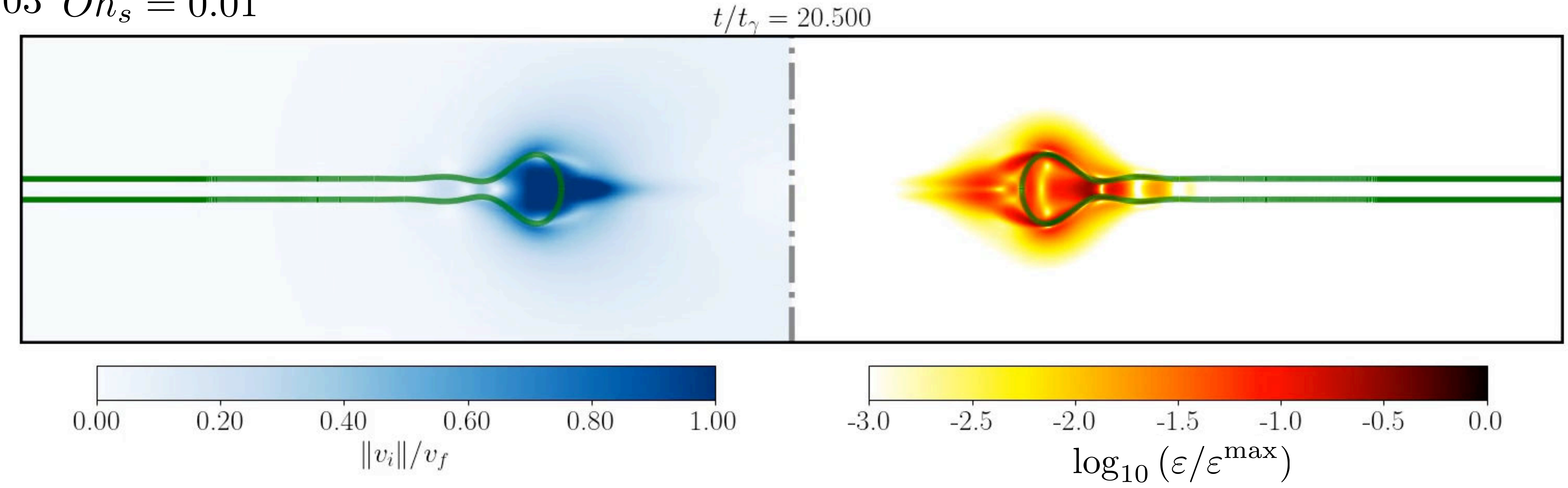
$$Oh_f = \frac{\eta_f}{\sqrt{\rho_f \left(2\gamma_{fs}\right) h_0}}$$

$$Oh_s = \frac{\eta_s}{\sqrt{\rho_f \left(2\gamma_{fs}\right) h_0}}$$

Retraction in viscous environment: Inertial limit

Control Parameters: $Oh_s = \dfrac{\eta_s}{\sqrt{\rho_f\left(2\gamma_{fs}\right)h_0}}$ $Oh_f = \dfrac{\eta_f}{\sqrt{\rho_f\left(2\gamma_{fs}\right)h_0}}$

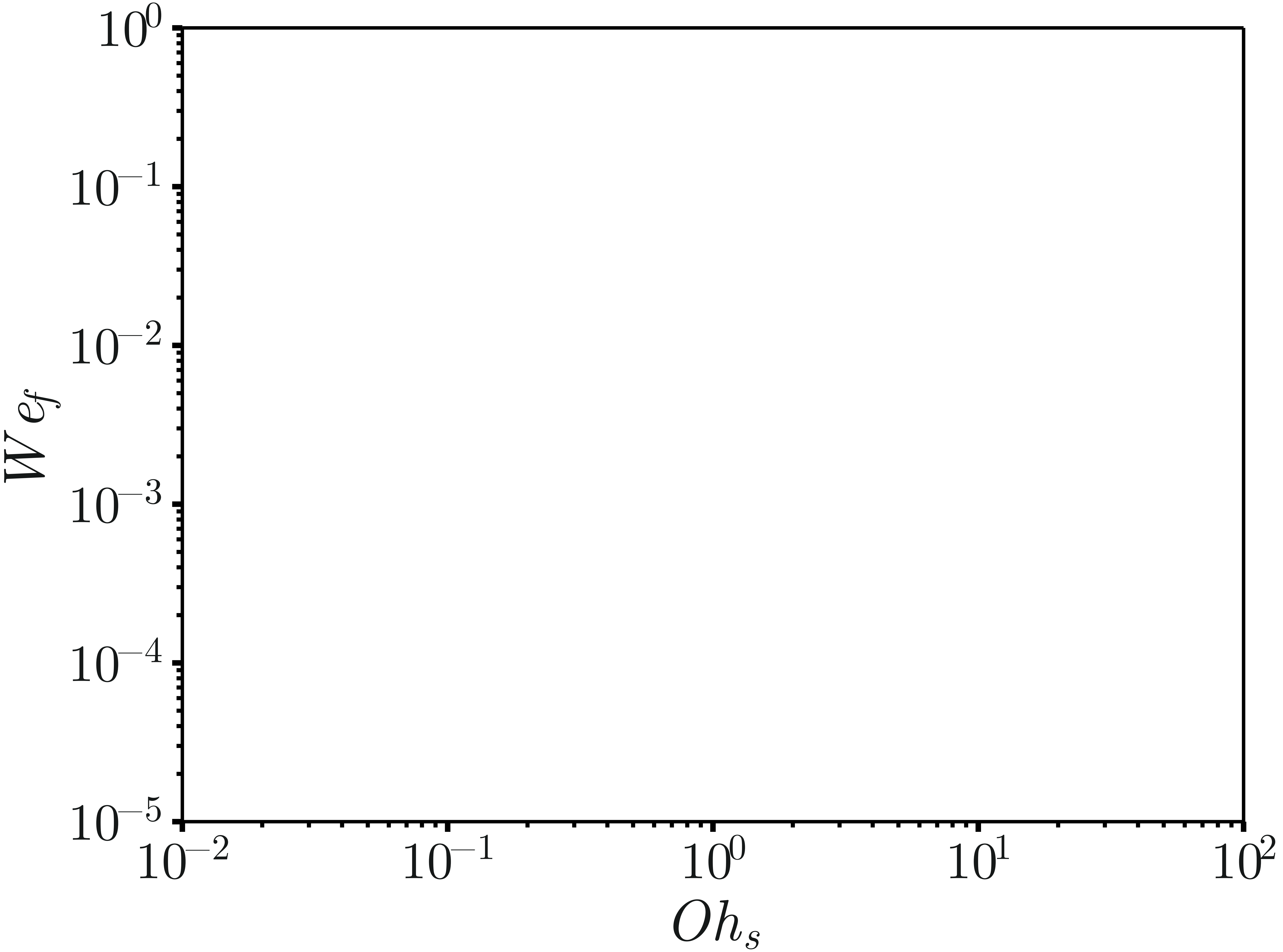
$Oh_f = 0.03$ $Oh_s = 0.01$



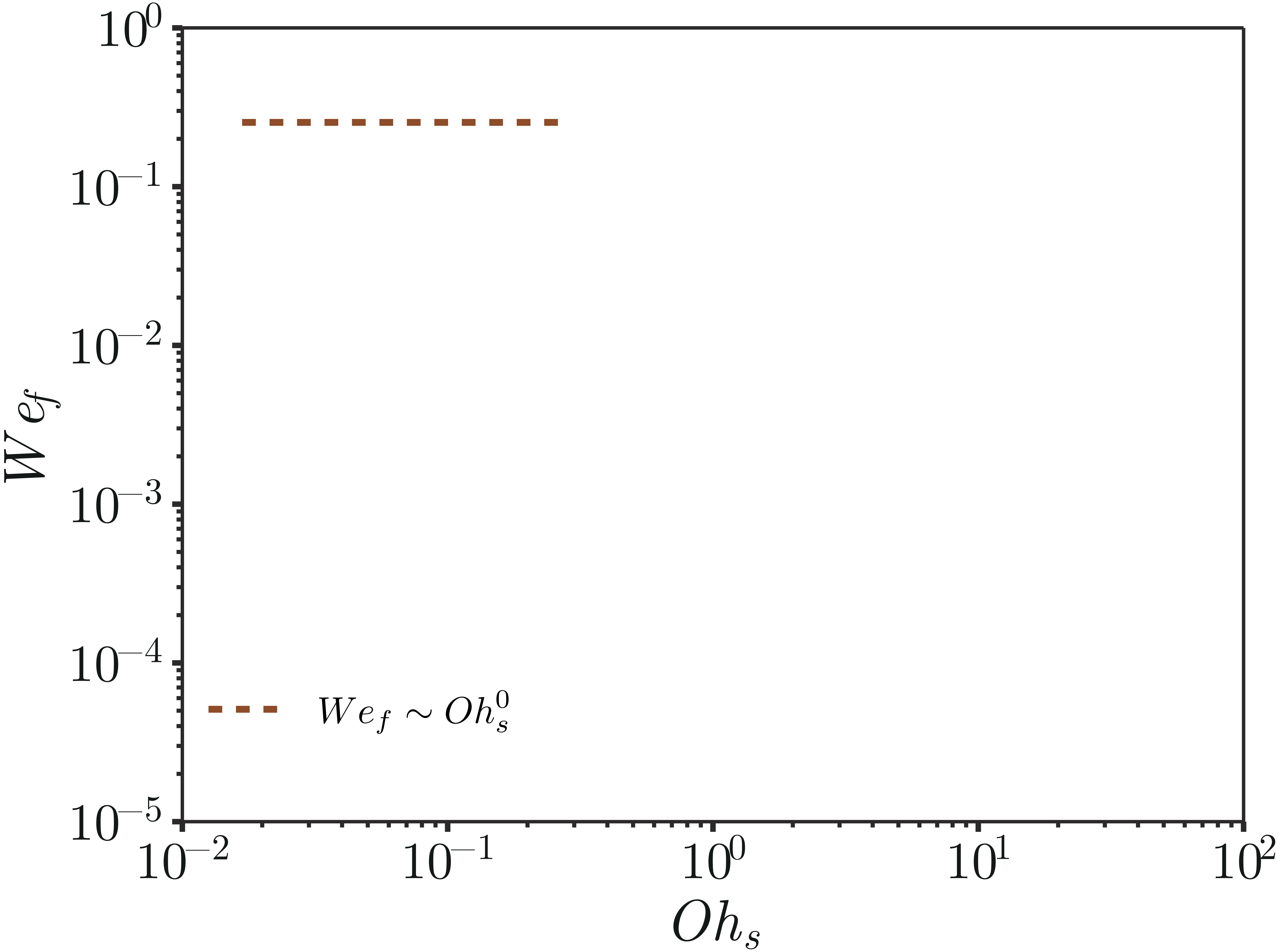
$$\varepsilon = 2\eta\,\mathcal{D}_{ij}\mathcal{D}_{ij}$$

Response: $We_f = \dfrac{\rho_f v_f^2 h_0}{2\gamma_{fs}}$

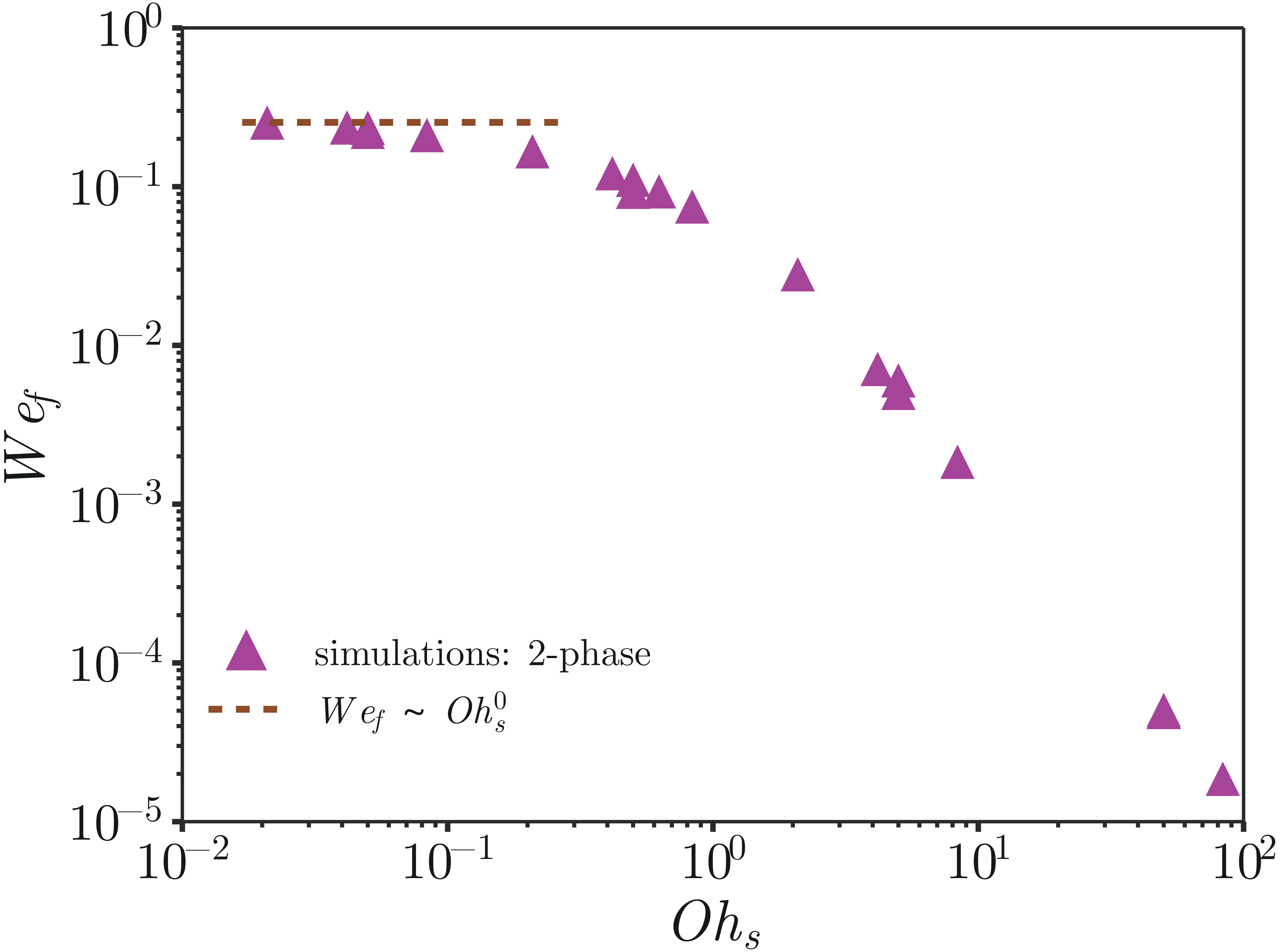
$$\mathcal{D}_{ij} = \frac{1}{2}(\partial_j V_i + \partial_i V_j)$$

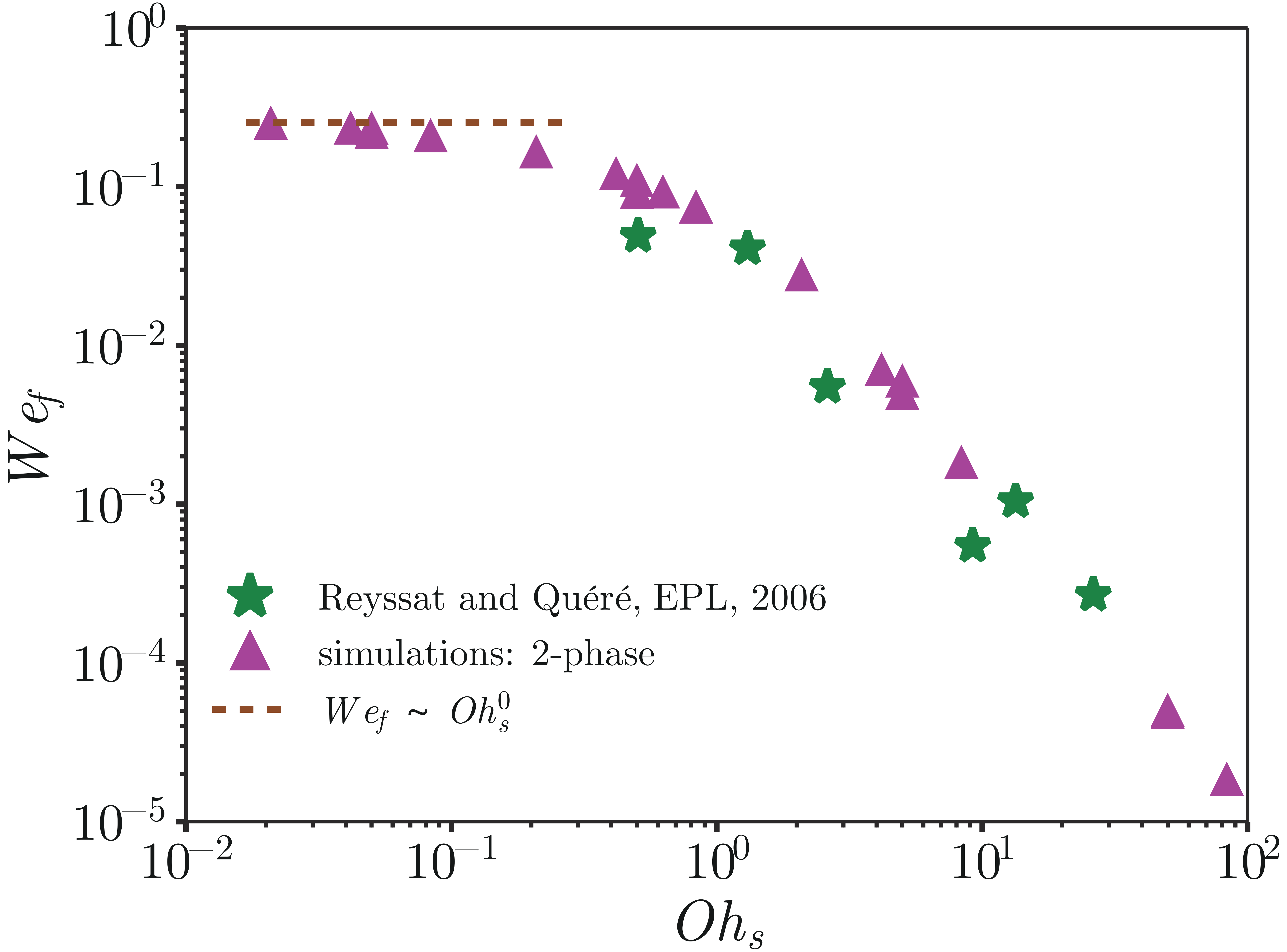


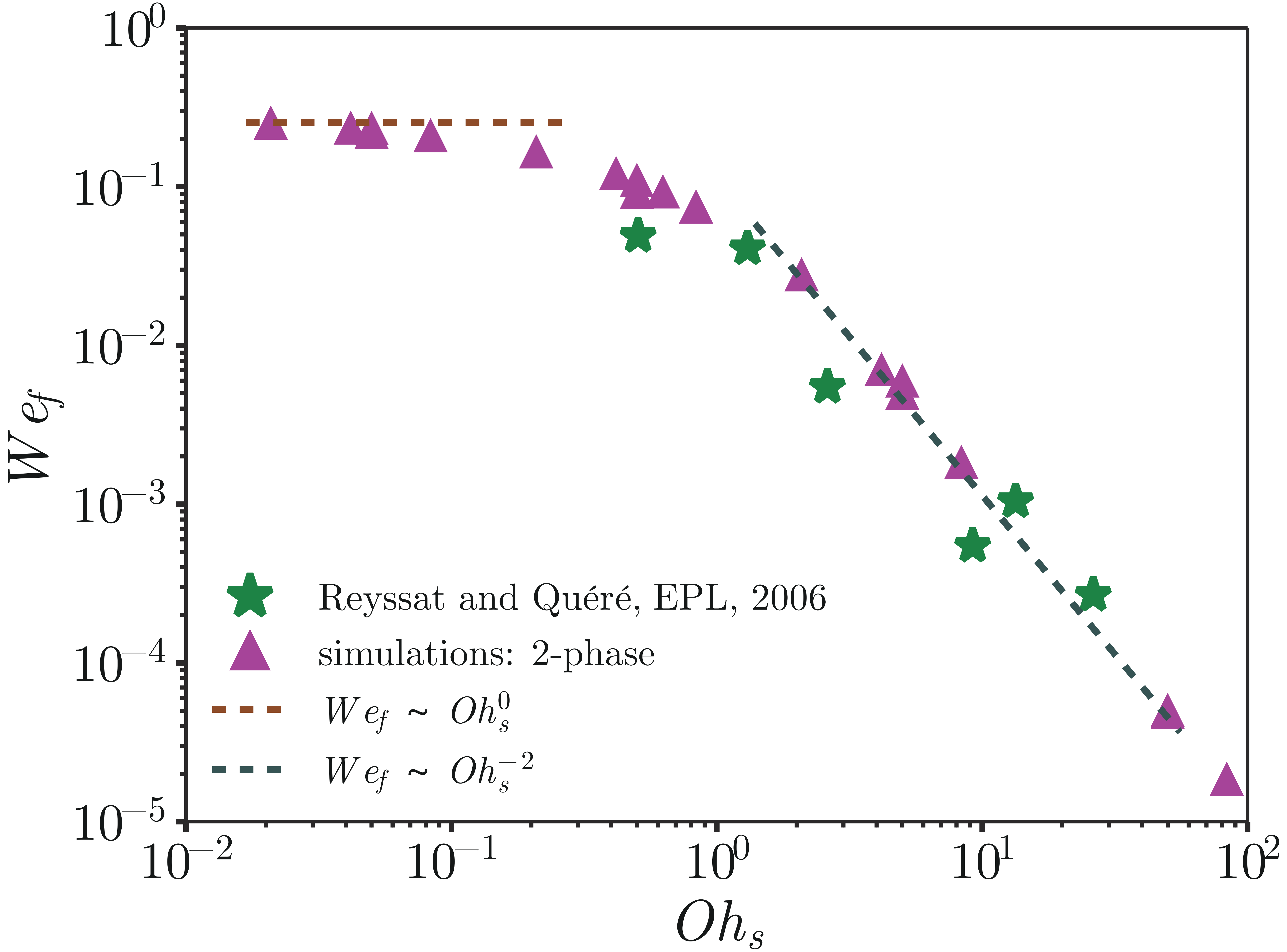
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
We_f
10^{-2}
10^{-1}
10^0
10^1
10^2
Oh_s



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
We_f
$We_f \sim Oh_s^0$
10^{-2}
10^{-1}
10^0
10^1
10^2
Oh_s


10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
We_f
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Oh_s
simulations: 2-phase
$We_f \sim Oh_s^0$

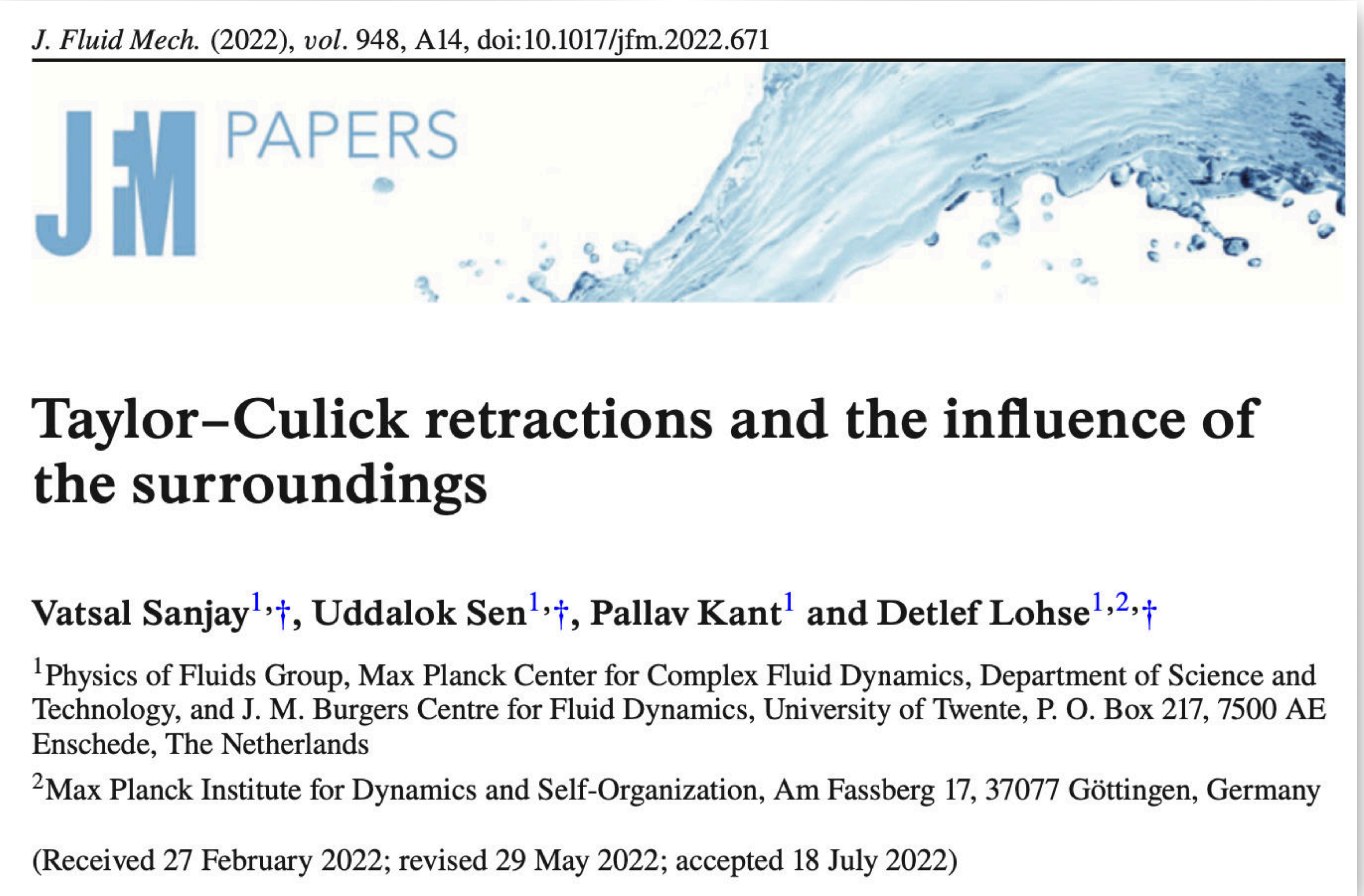

10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
We_f
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Oh_s
Reyssat and Quéré, EPL, 2006
simulations: 2-phase
$We_f \sim Oh_s^0$



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
We_f
10^{-2}
10^{-1}
10^0
10^1
10^2
Oh_s
★ Reyssat and Quéré, EPL, 2006
▲ simulations: 2-phase
$We_f \sim Oh_s^0$
$We_f \sim Oh_s^{-2}$

The story continues …

The story continues ...



J. Fluid Mech. (2022), *vol.* 948, A14, doi:10.1017/jfm.2022.671

Taylor–Culick retractions and the influence of the surroundings

Vatsal Sanjay[1,†], Uddalok Sen[1,†], Pallav Kant[1] and Detlef Lohse[1,2,†]

[1] Physics of Fluids Group, Max Planck Center for Complex Fluid Dynamics, Department of Science and Technology, and J. M. Burgers Centre for Fluid Dynamics, University of Twente, P. O. Box 217, 7500 AE Enschede, The Netherlands

[2] Max Planck Institute for Dynamics and Self-Organization, Am Fassberg 17, 37077 Göttingen, Germany

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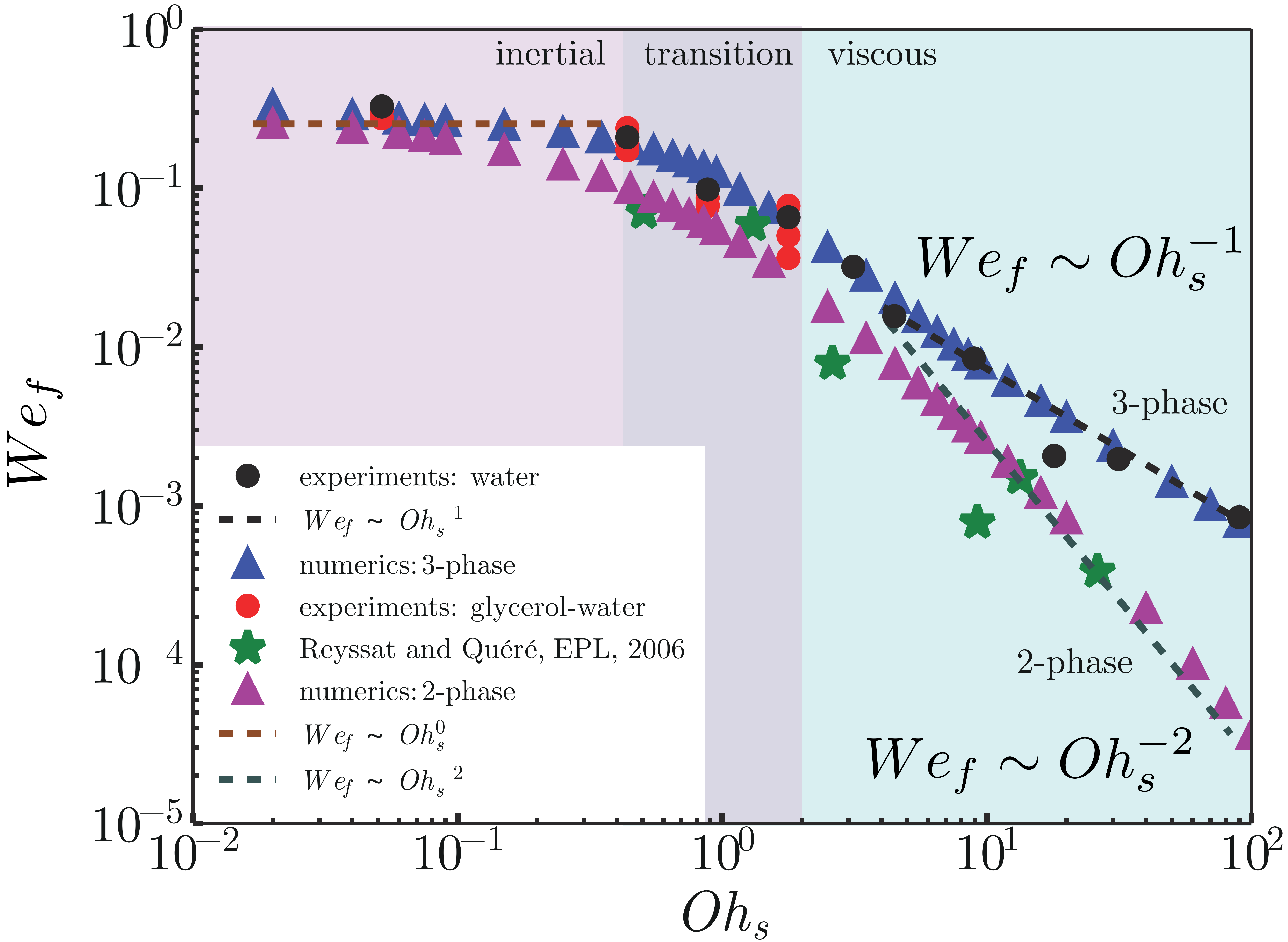
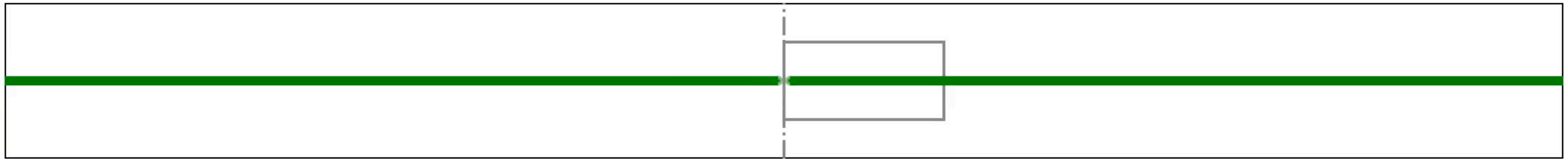
Water films may rupture at the oil-water-air interface, thus dispersing oil droplets further.

source: physics.stackexchange.com

The story continues ...



More to follow: **Elastic** Taylor-Culick



Jacco Snoeijer

Vincent Bertin

Alex Oratis

$$Ec = \frac{Gh_0}{\gamma} = 0.01 \qquad De = \lambda / \sqrt{\frac{\rho R_0^3}{\gamma}} \to \infty$$

One more thing...

Ph.D. positions across scales

Physics of Fluids

Ph.D. positions across scales

Physics of Fluids

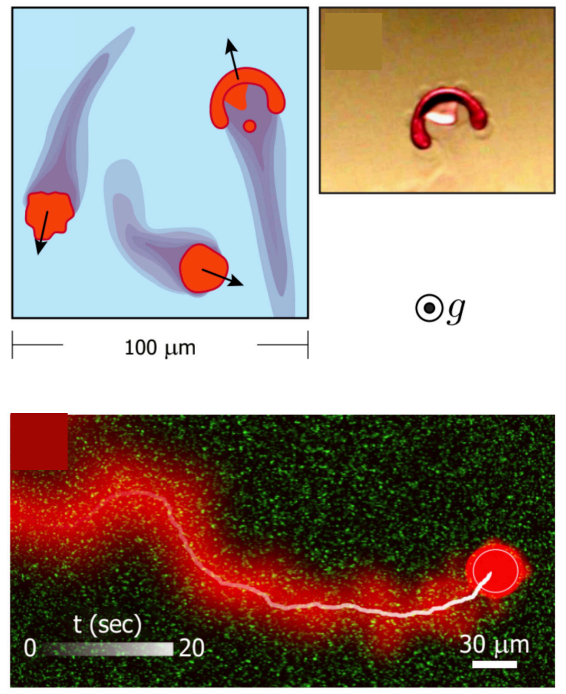
Flow for future

- Flow for Health
- Flow for Climate
- Flow for HighTech
- Flow for Environment
- Flow for Energy Transitions
- Flow for Agro & Food production

Ph.D. positions across scales

MultiMelt

Melting & Dissolution across scales



Physics of Fluids

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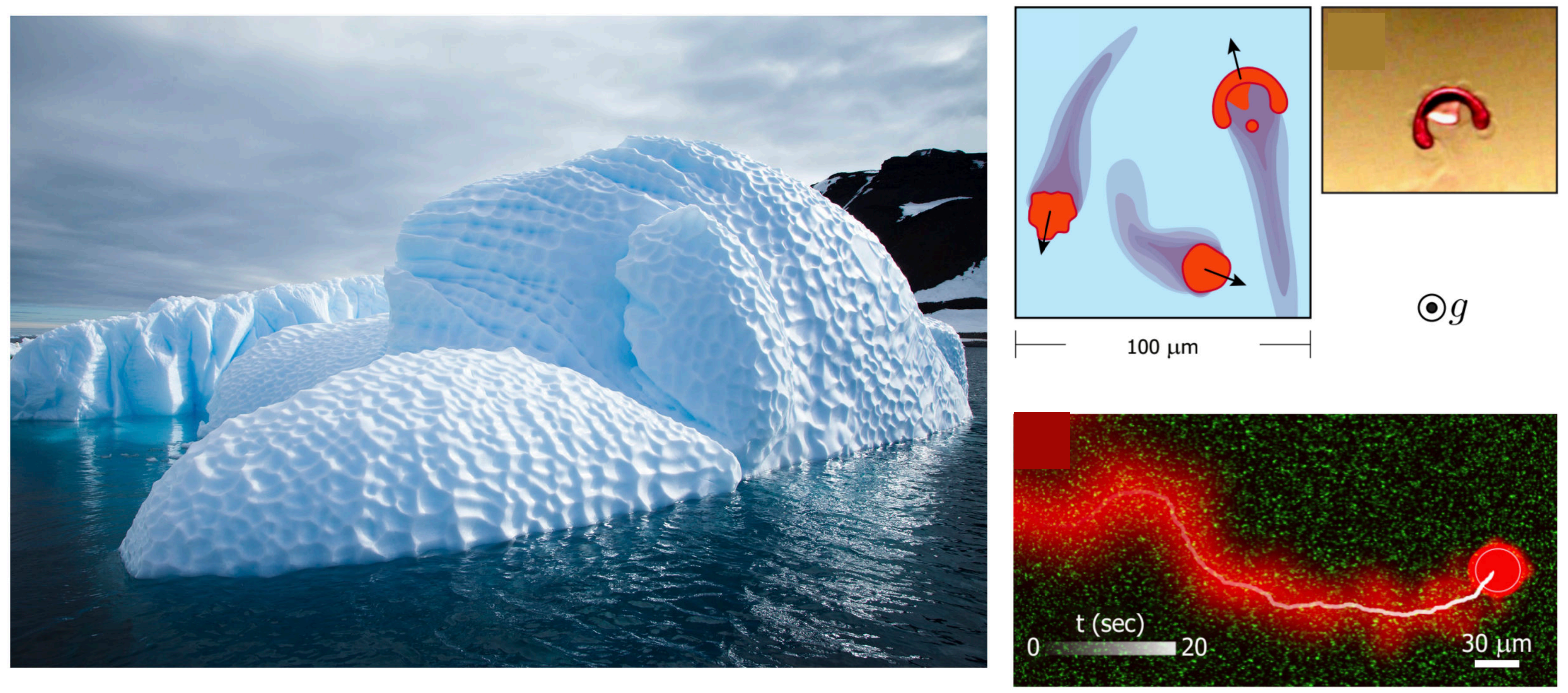
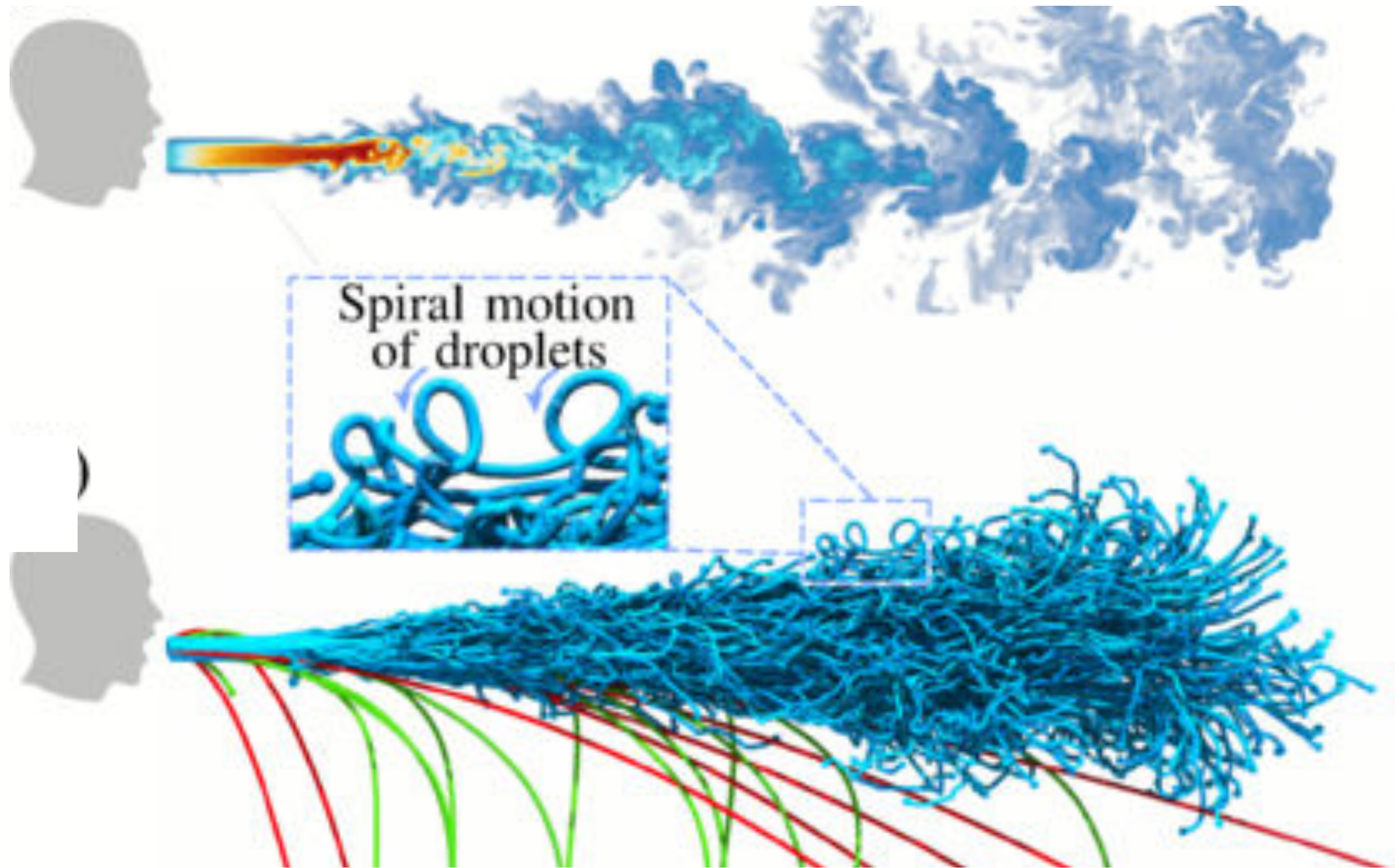


MIST

Mitigation Strategies for
Airborne Infection Control



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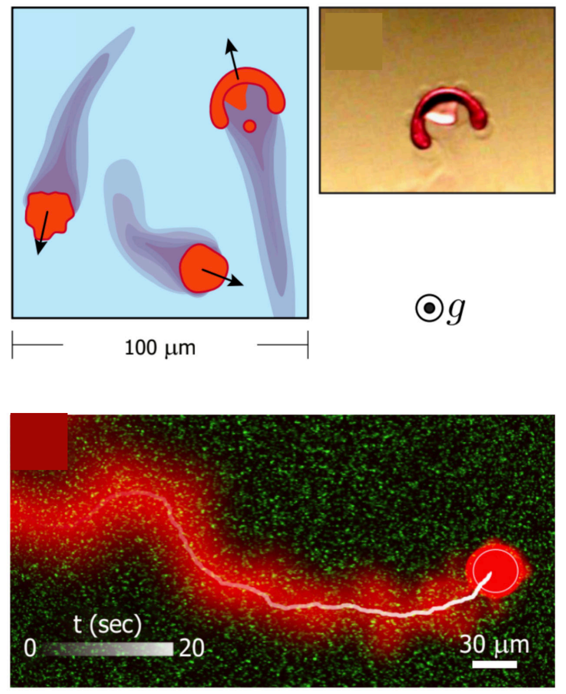

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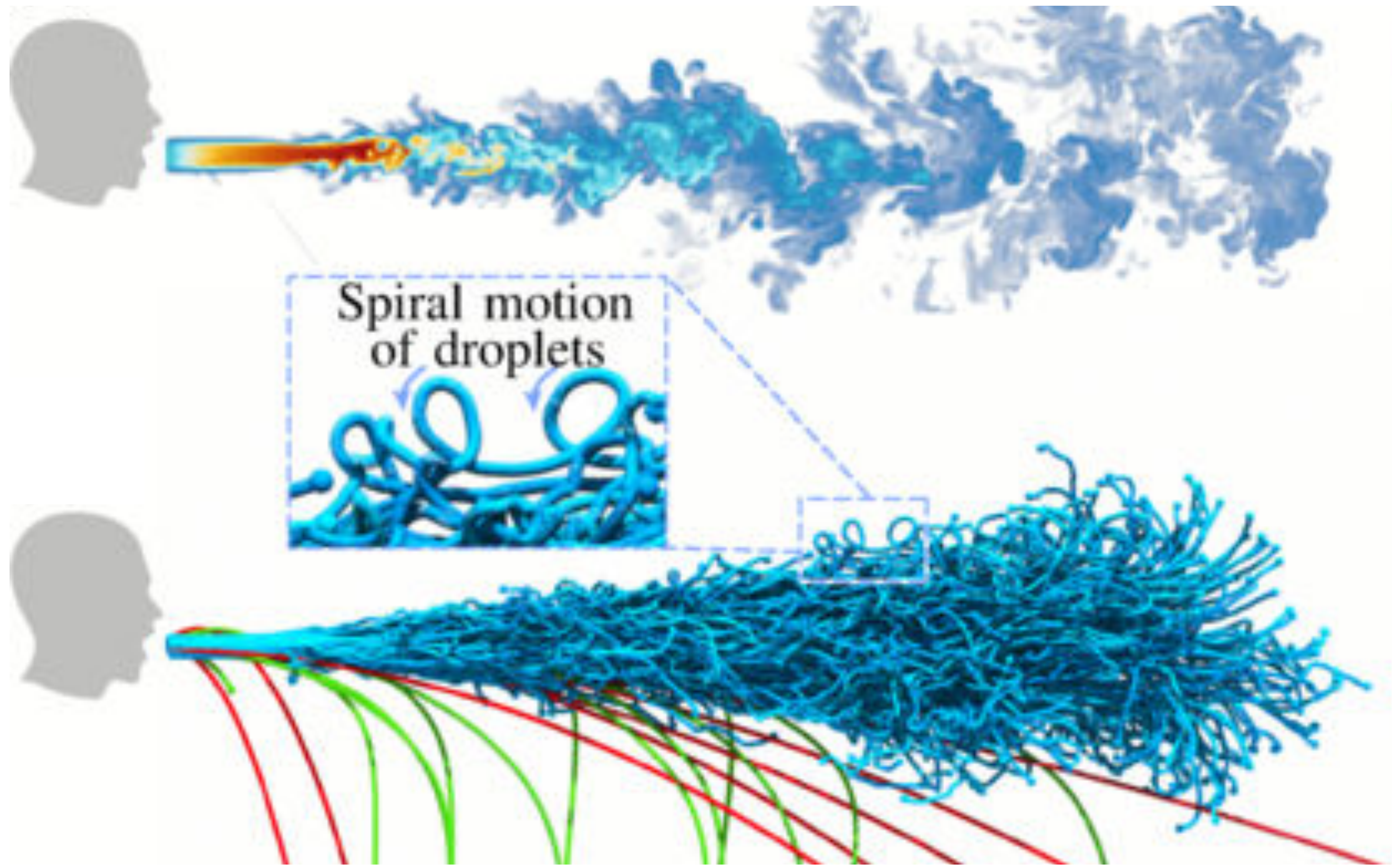


Physics of Fluids

Flow for future

Flow for Health

Flow for Climate

Flow for HighTech

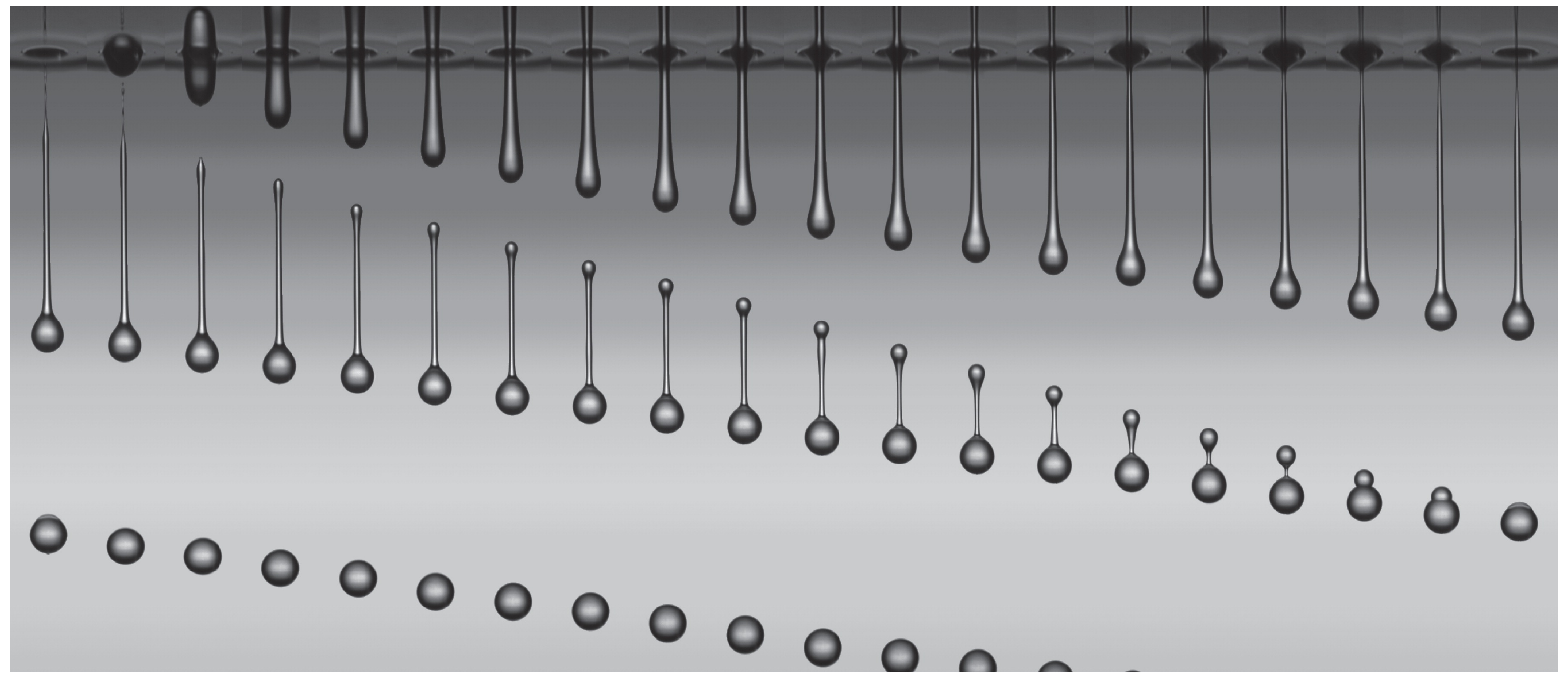
Flow for Environment

Flow for Energy Transitions

Flow for Agro & Food production

Fundamentals of Inkjet printing-II

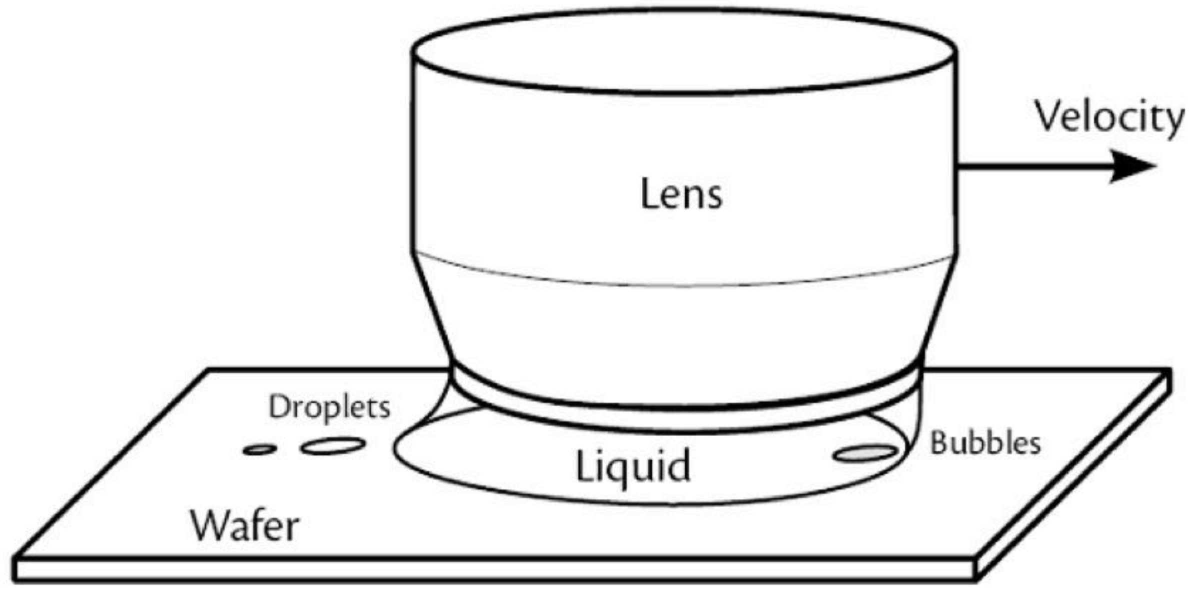
Physicochemical Hydrodynamics of Droplets

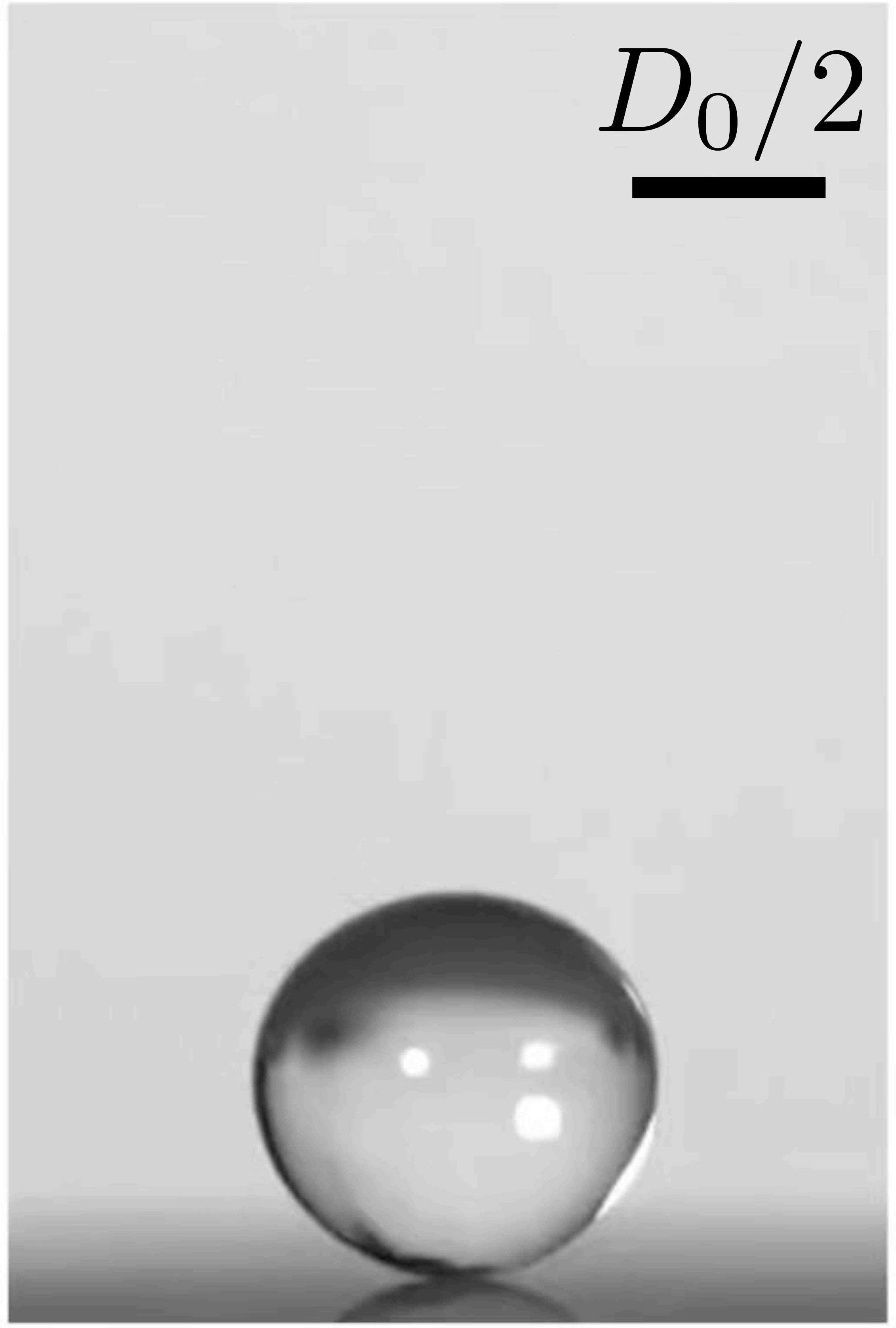


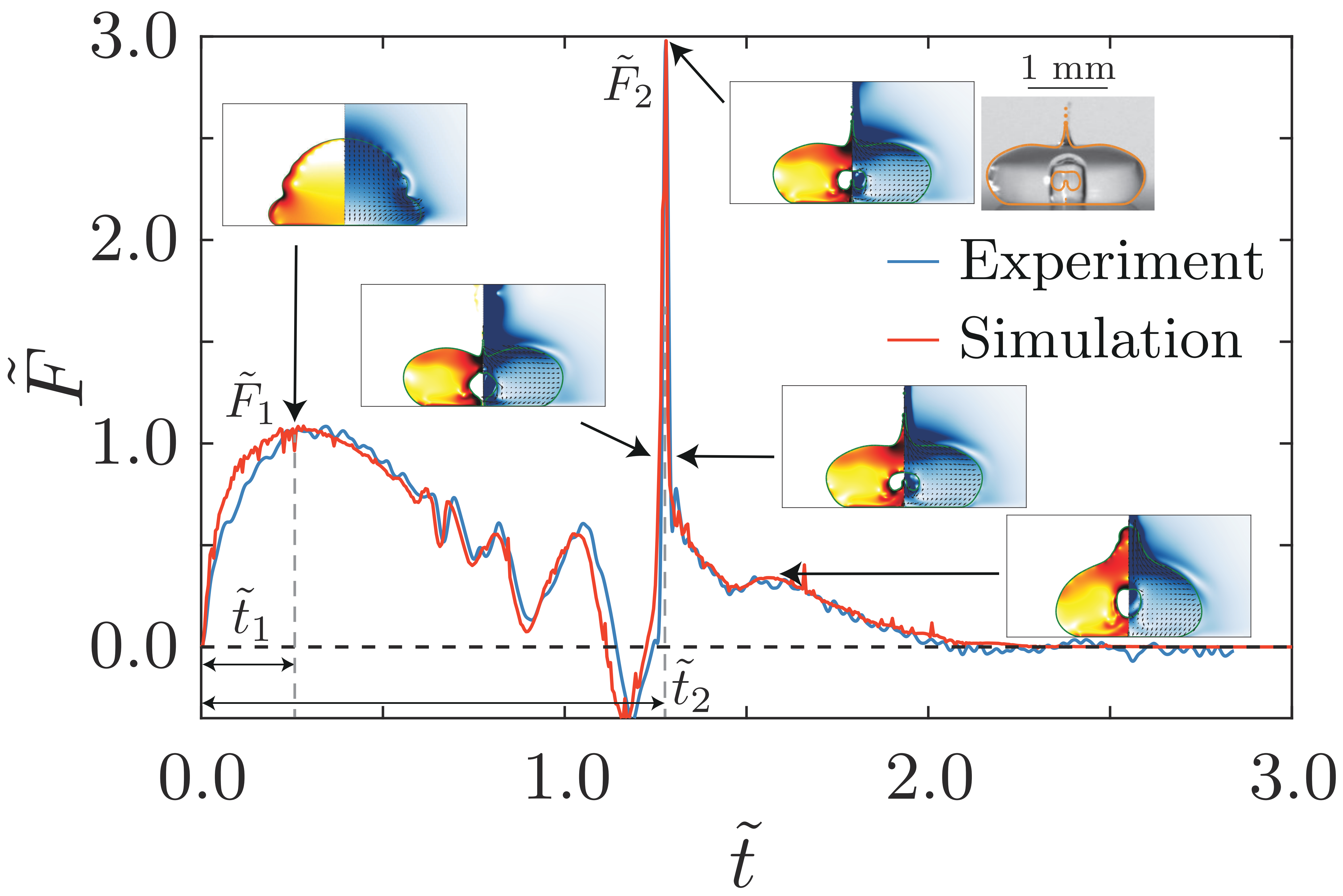
Canon ASML

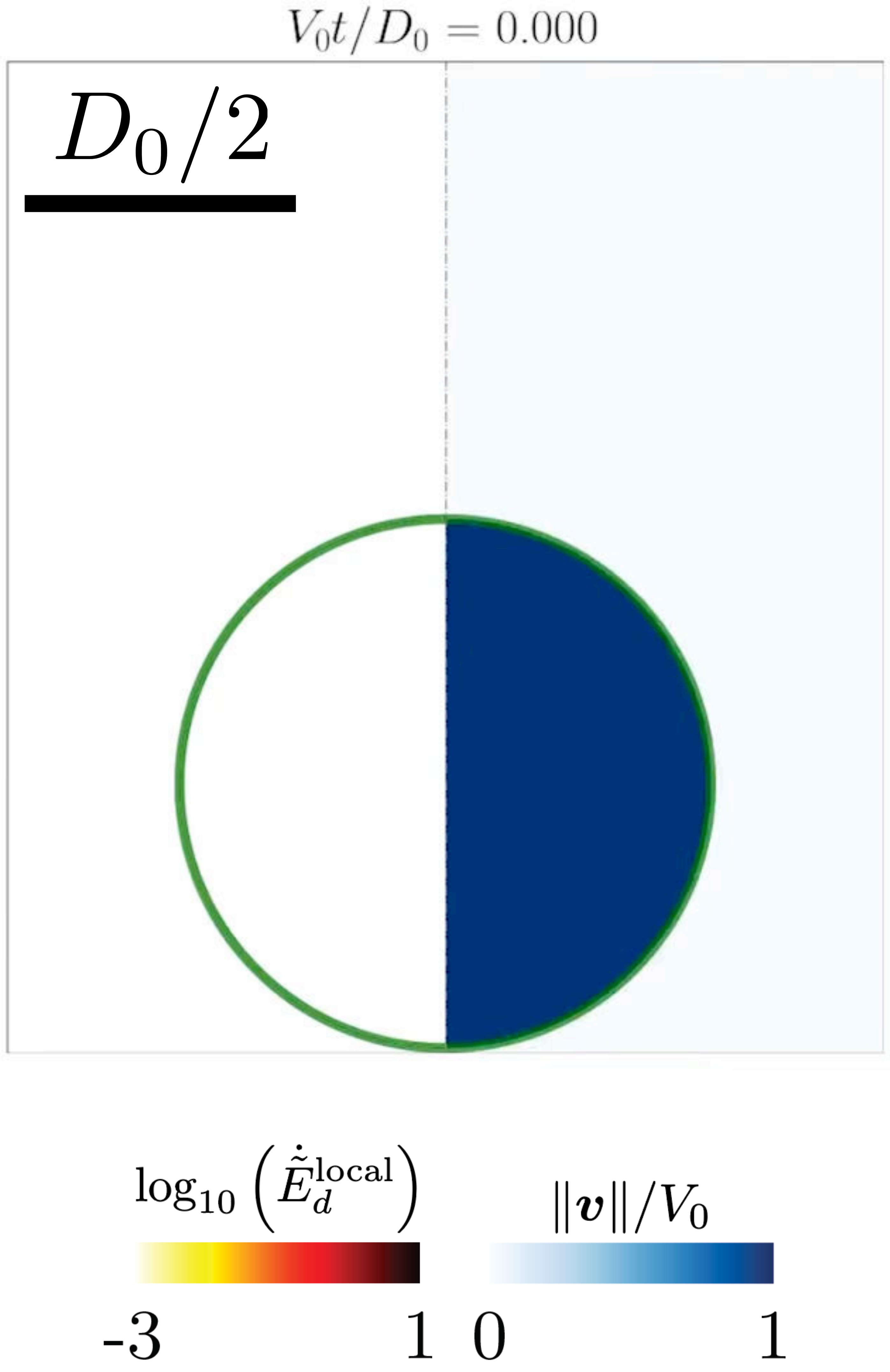
Contact lines

Inertial instability









Resources

Thank you!

contact@vatsalsanjay.com
vatsalsanjay.com
basilisk.fr/sandbox/vatsal/

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- Doris Vollmer (MPI-Mainz)

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OF TWENTE.

Physics of Fluids

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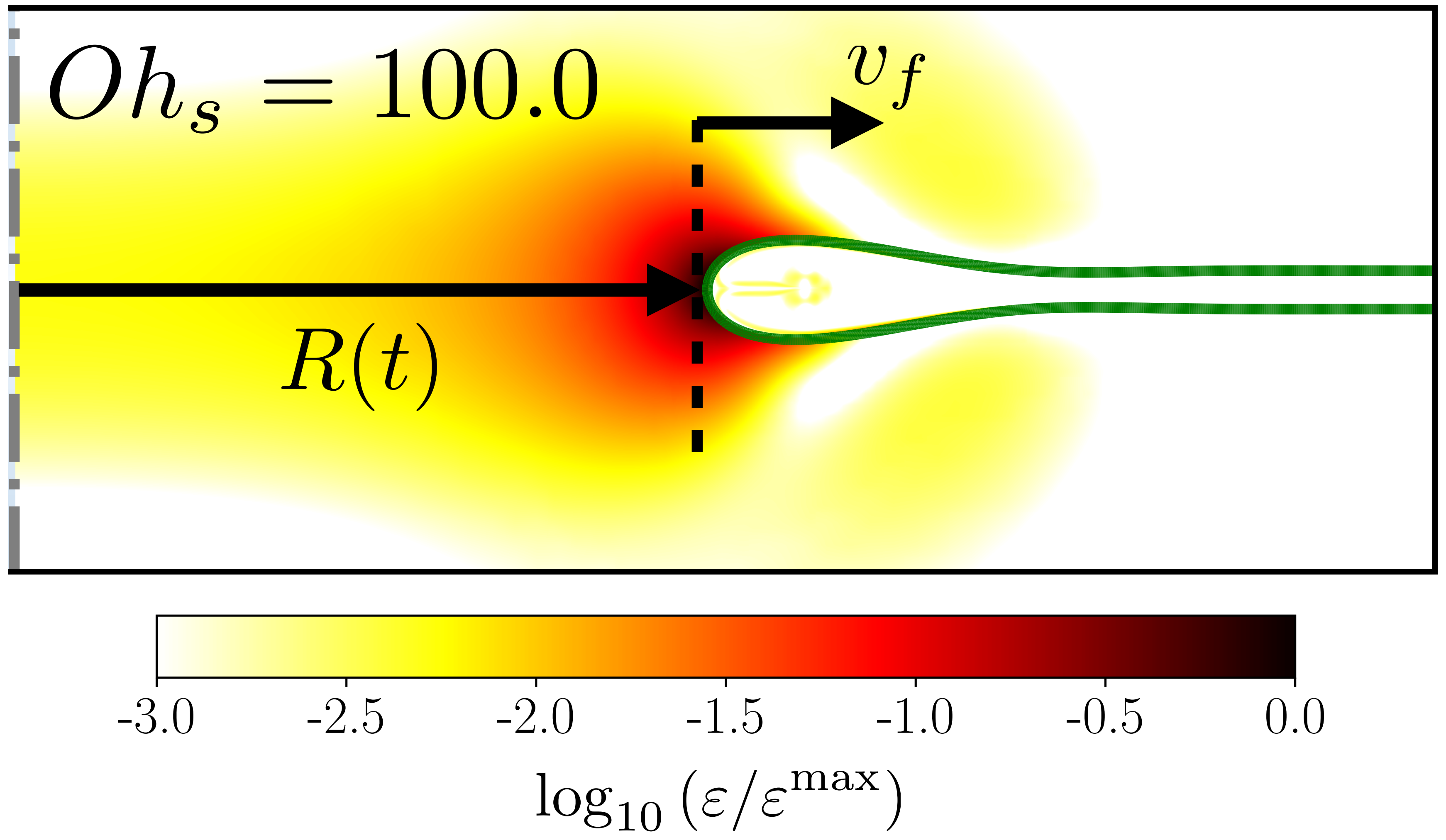
European Research Council
Established by the European Commission

How can we understand the scaling for retraction velocity?

$$\boxed{We_f \sim Oh_s^{-2}}$$

Dynamics: 2 phase

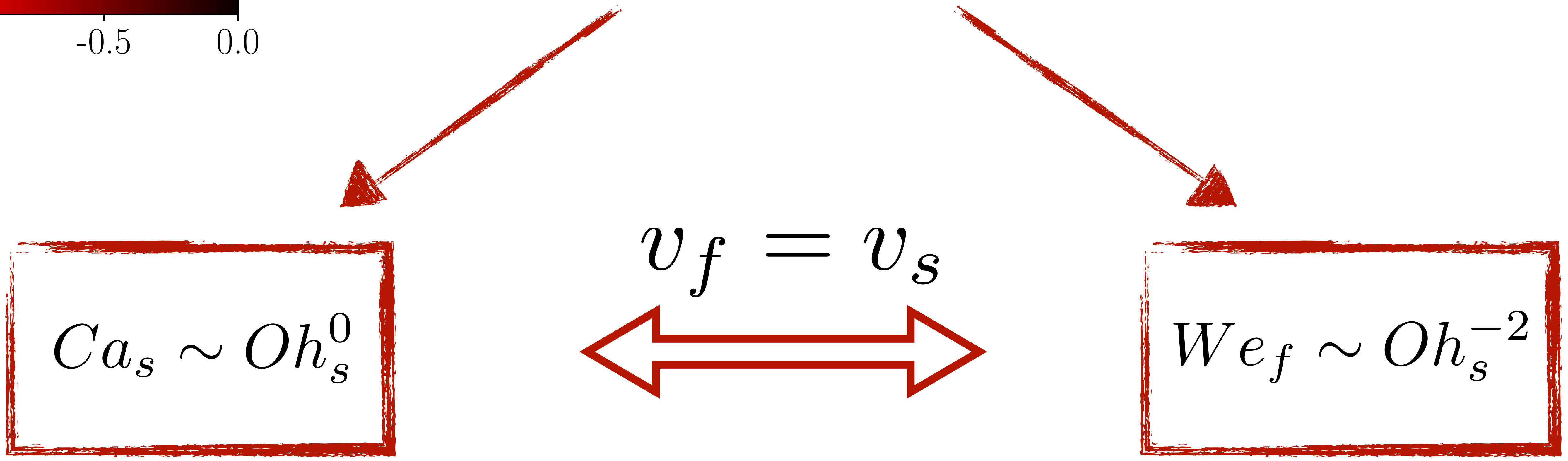
Capillary force during retraction vs. Viscous resistance



$$F_\gamma \sim F_\eta$$

Stokes flow/Oseen approximation

$$2\gamma_{fs} \sim \eta_s v_f$$



$$Oh_s = \frac{\eta_s}{\sqrt{\rho_f\left(2\gamma_{fs}\right)h_0}}$$

$$Ca_s = \frac{\eta_s v_s}{2\gamma_{fs}}$$

$$We_f = \frac{\rho_f v_f^2 h_0}{2\gamma_{fs}}$$

$$\boxed{Ca_s \sim Oh_s^0}$$

$$v_f = v_s$$

$$\boxed{We_f \sim Oh_s^{-2}}$$

Fraaije and Cazabat, JCIS 133, 1989
Reddy et al., PRF 5, 2020

2-phase Taylor-Culick retraction

$$Oh_f = \frac{\eta_f}{\sqrt{\rho_f\left(2\gamma_{fs}\right)h_0}}$$ independent